Gait Rehabilitation Techniques In Incomplete Cervical Spinal Cord Injuries

Theofilou I.[1], Pneumaticos S.[1,2]

[1]*Postgraduate Training Program, KAT Hospital, National and Kapodistrian University of Athens, School of Medicine, Athens, Greece*

[2]*3rd Department of Orthopaedic Surgery, KAT Hospital, National and Kapodistrian University of Athens, School of Medicine, Athens, Greece*

ABSTRACT

Incomplete cervical spinal cord injuries can lead to severe functional loss, with mobility deficits of the lower limbs and motor control. Contemporary gait rehabilitation techniques focus on the motor reprogramming of neuronic circuits. This systematic review aims to compare the results of different rehabilitation techniques, ranging from robotic exoskeleton systems, to new and improves weight- bearing systems, and other methods including virtual reality, on their ability to achieve measurable therapeutic goals.

Three electronic databases (MEDLINE, PEDro and Google Scholar) were systematically searched for clinical trials, up until May 2022. The following search terms were used: "Incomplete Cervical Spinal Cord Injury" AND "Gait Training" OR "Rehabilitation" OR "Exoskeletal assisted walking" OR "Lokomat" OR "Robot- assisted gait training".

Of the initial 2.411 papers, 54 were selected to be review for eligibility to this systematic review, leading to the final 20 that were included. The most common evaluation tools were 6MWT, 10MWT, TUG, LEMS and WISCI-II. In all 20 papers significant or very significant changes were noted between the time of the first assessment and the last. 13 of them noted statistically significant differences between the control groups and the intervention groups at the end of the trial period, regardless of the method used. In this systematic review, 409 patients were recruited for trials on robotic exoskeletons, 70 participated in Weight- Bearing trials, and another 55 completed trials on interventions including WBV, OLT and GRAIL. In regards to the use of a robotic exoskeleton system, 10 out of 13 trials noted statistical significant differences between groups, a result shared by 2 out of 3 trials on weight-bearing systems. Contemporary interventions using the latest technological advances, whether they be robotic exoskeletons, advanced weight-bearing systems or enhanced virtual reality, may contribute to a faster and more efficient gait rehabilitation of patients suffering from incomplete cervical spinal cord injuries.

Key words: Incomplete Spinal Cord Injury, Gait Training, Rehabilitation, Exoskeleton

CORRESPONDING AUTHOR, GUARANTOR

Theofilou I., Postgraduate Student of the Postgraduate Training Program, KAT Hospital, National and Kapodistrian University of Athens, School of Medicine , Athnes ,Greece.
Address: KAT Hospital , 2 Nikis Street, Kifisia , 14561.
E-mail: theofilou@outlook.com.gr

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Introduction

The incidence of spinal cord injuries is estimated to range between 40-80 new cases per million, with traumatic injuries accounting for about 90% [1-3]. The extrapolation of the prevalence to the global population shows that up to 500,000 patients per year face the consequences of spinal cord injuries. Traumatic spinal cord injuries overwhelmingly predominate over non-traumatic ones, the latter taking up to 10% of all spinal cord injuries [3]. In Greece, the epidemiological recording effort was carried out by KAT General Hospital, studying 1489 files of patients who came to the outpatient clinic of the hospital between 1987 and 1999. Their mean age was 33 years and the male/ female ratio was 4:1 (78,8% and 21,2% respectively)[4].

Incomplete cervical spinal injuries (cervical iSCI) account for 59% of all cervical spinal cord injuries [5]. These patients present deficits in balance, gait, sensation, as well as abnormal muscle tone, coordination and co-contractions [6]. Spinal cord injury occurs when a cause inflicts damage to one level of the spinal cord. The spinal level indicates the point at which the function of the nerves below is reduced or even suspended, depending on the extent of the damage. Spinal cord injury prevents information from being transmitted through nerve cells in both directions (motor and sensory pathways). Impaired information transfer can result in transient or permanent loss of mobility and sensation [7].

Spinal cord injuries, at the cervical level, are usually incomplete but, at the same time, due to the topography of the lesion, are amongst the most severe. Depending on the level of severity, these patients may experience difficulties with breathing, loss of mobility of upper and lower limbs, generalized weakness, loss of control of urination and defecation and muscle tone disorders [8]. A cervical iSCI, with the exception of injuries of the last myelotomy, leads to tetraplegia, i.e. the presence of neurological symptoms in the upper and lower limbs, and involvement of the trunk muscles, and usually falls under the AIS categories D to B [9,10].

Research in recent year has focused on the plasticity of neural tissue and its ability to form new connections and adapt post injury. Advances in rehabilitation, such as gait retraining using weight-bearing suspension treadmills, robotic exoskeletons and Functional Electric Stimulation (FES) are some of the new possibilities of technology used in therapeutic protocols, which mainly aim to reorganize, but also regenerate, neural circuits in order to improve patients' motor ability. Rehabilitation is focusing not only on compensating for any deficits, but more importantly on maximizing the potential for motor recovery [11, 12]. Current rehabilitation methods direct the processes of plasticity to create and enhance those synapses that serve the patients' functionality, and gait is capital to daily tasks and quality of life [13, 14].

Discussion

The negative consequences of a spinal cord injury do not result solely from damage to the grey and white matter. Neurons that are dead or in the process of necrosis activate the immune system, which sends macrophages and microglia to remove dead cells, thus triggering a series of inflammatory reactions, which in turn are responsible for the secondary damage that occurs after an injury [15, 16]. In an attempt to limit secondary damage, the body activates reactive astrocytes, which reduce inflammation and thus limit the area of damage by forming neuroglia [17]. This barrier, however, created by neuroglia can simultaneously limit neuronal regeneration, preventing neuronal growth, oligodendrocyte maturation and re-myelination attempts [15, 17].

Spinal cord injuries bring about structural changes, which cause the body to react, first by trying to regenerate and then by reorganizing the synapses and neural circuits that have survived. If the damage is such that there is a gap between the two ends of the nerve, then there is the possibility of axonal sprouting. A single axis may result in multiple collateral sprouting, of which few will be able to penetrate the zone of injury. The body's automatic response to damage can lead to both functional adaptations and maladaptation, examples of which are spasticity, dysreflexia and neuropathic pain. In some other cases, however, spontaneous reorganization can restore functionality following incomplete spinal cord injury, as in the case of Brown-Séquard syndrome (unilateral hemiparesis) despite the permanent loss of centrifugal nerve fibers [18].

Neuroplasticity is defined as the capacity for change,

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both at the functional and anatomical level of the nervous system, in response to training/retraining stimuli or in response to damage [15]. The process of neuroplasticity roughly involves the creation or rejection of synapses so as to maximize synaptic efficiency, and is the driving force behind learning, memory, and qualitative improvement in motor control. Until recently, the prevailing view was that synapses only change during the neurodevelopmental process, assuming that adult neural circuits are stable and do not change. Now, research has demonstrated that the CNS also makes modifications in adults, especially after injury [19].

Neuroplasticity is related to the strengthening and weakening of synapses, which occurs in response to incoming stimuli, but also to the timing of these changes. Thus, it is now known that the capacity for neuroplasticity depends on the composition of pre- and post-synaptic regions [19]. New synapses that contribute to the transient gratification of a stimulus, if proven functional, are further strengthened to require less stimulus to carry the energy potential, thus contributing to what is called longer-lasting plasticity [20] (Figure 1).

As can be understood, the smaller the extent of the damage, the greater the effects of plasticity can be expected through restoration. Therefore, after an incomplete spinal cord injury, better results are expected through rehabilitation than after a complete injury at a corresponding spinal level.

Therapeutic strategies for gait rehabilitation after Incomplete Cervical Spinal Cord Injury

The plasticity of the CNS is a remarkable feature, since it allows for relearning and recovery after injury. However, without the guidance of plasticity from rehabilitation, the likelihood of functional recovery is clearly reduced [15]. Rehabilitation interventions are studied for their effect on functionality and therefore the structural changes they can bring about in the spine following injury. These changes do not simply occur through movement, but are directly dependent on functional activity, i.e. muscle contraction is not sufficient, but a combination of functional movements are required to achieve a specific action, such as walking or Activities of Daily Living (ADLs) to make a record in the CNS [21]. By moving the body to achieve motor activities, the spine receives stimuli about the quality of movement from sensory neurons in the skin, muscles and joints. The neurons of the posterior horn receive these impulses from the periphery and promote or reject new synapses. In addition, the process is controlled through feedback from centres higher up in the spinal cord, which are co-responsible for the quality of movement (cerebellum, basal ganglia, motor cortex, etc.) [15, 22].

The main therapeutic strategies, so far, in the field functional rehabilitation of incomplete cervical spinal cord injuries are therapeutic exercise - with the use of suspensions or exoskeletons, electrical stimulation and the recently emerging field of the use of Brain-Computer Interface (BCI) technology. Exercise can improve the functionality of spinal motor neurons and remodel the cerebral cortex by increasing the neural activity of specific neurons, leading to the strengthening of specific neural pathways [12, 23]. Electrical stimulation can regulate the excitability of spinal circuits, aid muscle strengthening and promote the process of plasticity [4=24, 25]. Finally, the brain-computer interface is under investigation for the potential it may provide in translating brain activity into movement [22].

Therapeutic Exercise: Therapeutic exercise can reduce apoptosis rates, promote neuronal regeneration, reduce inflammation and increase those spinal functions that have not been affected by the injury [26]. In addition, exercise can reduce the size of a potential syringomyelia and the surface area of the glial fossa, thereby increasing the potential for axonal growth, synapse remodeling, and the axonal myelination process [27]. Exercise can affect unaffected spinal cord parts and muscles and promote remodeling of neural circuits to achieve functional movement [28]. In fact, it is thought that maintaining skeletal muscle function may regulate the normal metabolic function of spinal neurons and have a positive centripetal effect on the cerebral cortex [29].

Intervention techniques begin immediately after admission to hospital and in the acute phase are mainly aimed at preventing seizures, maintaining range of motion and preserving respiratory capacity. Research has shown that early mobilization, including stretching, passive and active exercises (depending on the level of injury), has a positive effect on pulmonary function as well as muscle strengthening. For this reason, in the acute phase, exercise should be performed close to the patient's strength levels for maximum results [30]. In the subacute and chronic phase, effort is focused on moving as independently as possible. For patients with an incomplete C4-C8 injury, even independent transfer from bed to wheelchair is a challenge, so retraining gait requires sophisticated equipment. Even the use of this equipment, however, requires the patient to maintain weight at normal levels, increase aerobic capacity and increase muscle mass [30].

Alternatives to traditional strengthening methods are also being explored, such as the use of vibration to improve spasticity (In et al, 2018), and the use of therapeutic water pools, in which buoyancy helps to significantly reduce the load on the lower limbs [31].

Advances in technology have paved the way for new applications in the field of gait rehabilitation for patients with cervical spinal cord injury, with the aim of achieving safe and independent mobility without a wheelchair. For these patients, simple orthotic means are not sufficient and the use of robotic technology is therefore required. The robotic devices currently in use can be categorized into exoskeletons that attach to a fixed point, over a walking treadmill and exoskeletons that can be worn and assist walking anywhere. Fixed exoskeletons, such as the Lokomat, are programmed for walking on a treadmill, where robotic limbs facilitate hip and knee movement and part of the patient's weight is held in place by suspension. In contrast, mobile exoskeletons support patients in retraining upright positioning, weight transfers and gait on different surfaces, even stairs. The choice of the most appropriate exoskeleton is related to the level of impairment and the implied treatment goals that the rehabilitation team has for the patient. In patients with incomplete cervical spinal cord injury, the use of fixed robotic systems is predominantly preferred [9,10,32,33].

Electrical stimulation: Electrical stimulation can contribute to axon growth and myelin formation [34] and stimulate neurons to induce muscle contraction [2]. The stimulation pathway of neuronal circuits is regulated by electrical stimulation, such as Epidural Electrical Stimulation (EES), Functional Electrical Stimulation (FSE) and Transcutaneous Spinal Cord Stimulation (tSCS) [35]. One clinical study reported that EES can promote recovery of the spinal kinesthetic network after spinal cord injury by producing coordinated and sufficiently strong electrical activity in the muscles involved in posture and gait [36]. In another clinical study, EES was able to reactivate voluntary movement control in patients with a severe clinical picture after spinal cord injury [25]. Finally, tSCS is a novel therapeutic approach that can stimulate the spinal cord through the skin. In a recent study, it was reported that using this method to obtain mobility and sensation in the upper limb of a geriatric patient with incomplete spinal cord injury, which gives hope for its use in promoting neuroplasticity, even in the geriatric population [37].

Brain-computer interface: With the advancement of technology in recent years, the field of research has opened up to the use of advanced computers. The operation of these systems is based on the recording of brain waves (via an encephalogram) and their decoding by a computer, which makes the algorithm matching the movement that the patient would like to make. The computer then sends the appropriate signal either to robotic systems or to the muscles themselves, via electrodes, to induce the desired movement [38,39].

Although, to the best of our knowledge, no research has been published on the use of this technology for gait retraining in people who have suffered spinal cord injury, there are several literature reports on patients with stroke. Their results are encouraging, which may mean that the scope of application of this technology will be extended to other categories of patients with CNS lesions.

Virtual Reality and Gait Rehabilitation: Recent technological advances have allowed rehabilitation specialists to utilize innovative methods in their therapeutic protocols. One such method is the use of virtual environments [40]. The concept behind it is that technology simulates real- life environments (walking in the city or on an uneven terrain such as a hill or a forest) for the brain. At the same time the actual training takes place in a completely controlled, and

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therefore, safe environment, and patients are not at risk of fall and/ or injury. Virtual environments can help train gait and balance safely and, at the same time, push the patient to explore the extent of their capabilities and even improve them, while practicing in a diverse and motivating way [41]. Different modules of training allow the patient to learn how to avoid stable and moving obstacles, step with more precision and react to possible every- day situations that may occur in a normal surrounding (i.e. crowded city places). More importantly, adapting ones gait to the environmental conditions that are out of control, increases functionality in Activities of Daily Living and reduces the risk of fall [41, 42]. In patients with iSCI, precision stepping has been proven to improve gait by improving walking variables such as speed and balance [43].

Conclusions

Technological advances can provide new alternatives for gait rehabilitation after iSCI. Robotic exoskeletons, advanced weight-bearing systems, FES, brain-computer interface and virtual reality are all employed and screened to offer more efficient recoveries, and a better Quality of Life. More research is needed to determine what could be an optimal protocol for gait rehabilitation after cervical iSCI, given the complexity of the clinical implications the lesions' topography presents, but the current the recent research findings are encouraging. Ⓐ

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