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Review Article

# Researching the recovery of locomotor activity after traumatic conditions of the lower limb

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## Summary

The ability of living organisms to navigate their environment is essential for survival. In scientific literature, this ability is known as locomotion, with walking being the primary mode of human movement. Our focus on the potential for independent movement within the environment arises from the high incidence of lower limb injuries and the significant number of patients requiring assistive devices to improve their walking ability, which is why we are conducting this review. The gait cycle begins with the stance phase, marked by heel contact, and consists of five subphases: initial contact, loading response, mid-stance, terminal stance, and pre-swing. The subsequent swing phase includes three subphases: initial, mid, and terminal swing. Key characteristics for assessing gait parameters are categorised into spatial and temporal indicators. Spatial indicators include stride length, step length, stride width, and foot angle, while temporal indicators encompass stance and swing phases, cadence, stride and step time, single and double support time, and speed. Human gait analysis has been done using numerous research methods, with traditional approaches being semi-subjective. Recent technological advancements have led to devices for objective evaluation, classified into non-wearable and wearable sensors. Our research focused on gait parameters to monitor recovery in patients with lower limb injuries and evaluated the G-WALK model, a wearable inertial sensor device which effectively registers spatial and temporal gait parameters.

Numerous unanswered questions about gait recovery after lower extremity trauma motivated this review.

**Key words:** G-WALK, gait cycle, injury, trauma, walking, wearable device



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## Introduction

The ability of living organisms to move through the environment is essential for their survival. In scientific literature, this ability is defined as locomotion and different forms of it are known. Locomotor activity can be carried out on land, air, or water. Different forms of locomotion are known, such as walking, running, swimming, jumping, flying, crawling, sliding, etc. The most common mode of locomotion for humans is walking. It is a natural motor act that allows the movement of the human body across the environment (Vacheva 2017). One of the main features that defines the human form is the vertical position of the spine and movement across the environment by using the lower limbs.

This ability helps an individual to change their habitat and adapt more easily to changing conditions, which proves to be a helpful skill and helps develop the human species over the years, improving the movement in a vertical position relative to the support. In addition to the change in the skeletal-muscular structure, the fine motor skills of the upper limbs also develop. Years later, several scientific studies found that humans stand on lower limbs to reduce energy expenditure when moving (Lacquaniti et al. 2012).

Our interest in the possibility of independent movement across the environment is based on the frequency of lower limb injuries and the significant number of patients in whom the use of aids is necessary to support and facilitate walking. As a result of the trauma, the mobility of an injured person is limited, the ability to self-care is impaired, work capacity is reduced, and social contacts are difficult. As a result, his quality of life is diminished (Kohler et al. 2017; Singaram and Naidoo 2019). In the available literature, all the main spatiotemporal parameters of gait in healthy people and the ways and methods of their registration are described in detail. Publications on locomotor activity in athletes prevail (Brogli and Petkova 1988) because the load of the lower limbs is important. Numerous studies have been done on large groups of people to establish average norms of individual gait characteristics. The kinesiological principles of normal walking cycles are well understood, as is the pathokinesiological knowledge related to various lower limb injuries and diseases that result in abnormal gait patterns. For achieving a faster and more complete functional recovery after a traumatic condition of a lower limb, it is necessary to study the results of physical and rehabilitation treatment, which aims to stimulate and accelerate the recovery of a person's locomotor capabilities and improve the quality of life and ability to work. Modern scientific and practical developments report the latest achievements of science, technique, technology, and practice, necessitating their inclusion in clinical research, analysis of the data obtained, and their application in daily clinical practice.

The practice in the field of medical rehabilitation shows that when it becomes impossible to walk independently as a result of trauma or disease of the lower limbs, patients become immobilised, their social contacts are limited, and their quality of life deteriorates (Singaram and Naidoo 2019). These problems motivated us to carry out the present study and analyse the results achieved in recovering gait parameters in various post-traumatic conditions that disrupt normal gait.

From a kinesiological point of view, walking can be described as changing one's location in the environment through coordinated rotatory movements of its joint segments. Walking engages the musculoskeletal system, although the lower limbs carry out the main movements. Human gait has highly pronounced individual characteristics. Each person's gait is unique, like fingerprints. Walking is a complex motor process characterised by three main components: transferring the weight of the body from both to one lower limb, transferring the body's centre of mass (COM) forward in front of the supporting lower limb, shortening the non-supporting limb (the swing limb), which appears to be relatively sufficient to provide an opportunity to carry it forward and meet the support (Crowe 1995). In humans, walking is a motor habit that is a highly automated process, and movements along with muscle involvement are incredibly economical. In practice, after the body's COM is brought forward in front of the supporting limb, the body "staggers" forward, and its balance is restored by meeting the support of the swinging leg. If the extension of the swing leg is impeded, one loses balance and falls. In other words, walking is alternately breaking and restoring balance. At the moment of "staggering," the force of gravity is used, which helps move the body forward, thus reducing the necessary muscle effort (Popov 2009).

## Gait cycle

When studying and analysing locomotor activity (walking), attention should be directed to three moments – starting, walking cycle, and stopping. The walking cycle covers all motor actions between two consecutive touches of the heel of one of the limbs to the support area, i.e. when making a stride. Each stride consists of two steps – with the left and right limbs. Step length is measured by the distance between the two feet when both limbs are in contact with the support (double support period). The motor actions of each of the lower limbs (left and right) go through two main phases: a stance phase (when the foot is in contact with the support) and a swing phase (when the foot is not in contact with the support) (Fig. 1). The stance phase begins with the initial contact of the foot of the corresponding limb with the support. During normal walking, each limb is in the stance phase for about 60% of the entire cycle. When both limbs are in the stance phase, a period of double support subphase is observed (both feet are in contact with the support). For about 40% of the stride time, each of the lower limbs bears the weight of the body alone – a period of single support (Mirelman et al. 2018).

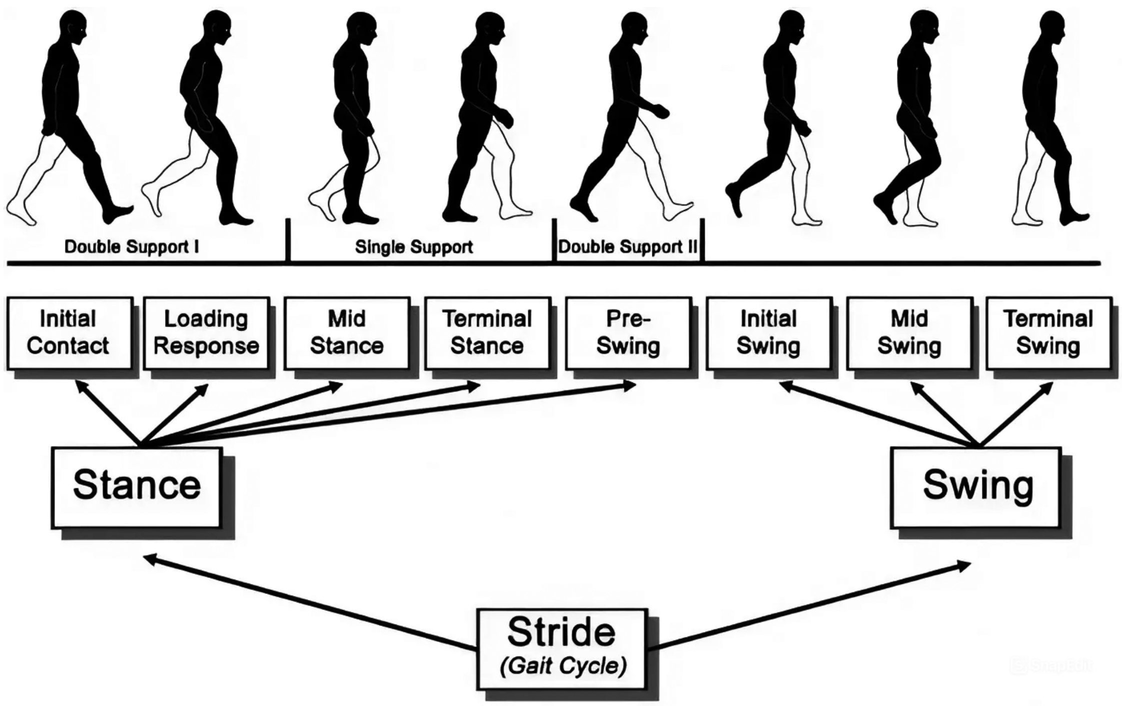



**Figure 1.** The gait cycle.

The gait cycle begins with the stance phase, in which initial heel-to-stance contact occurs and is divided into five subphases (initial contact, loading response, mid-stance, terminal stance, and pre-swing). In a normal gait, the heel must meet the support initially. The ankle is in a neutral joint position. At the initial contact with the support, the knee joint is almost fully extended, after which it flexes slightly under the concentric action of the flexor muscles. The trunk is upright, rotated to the supporting limb, and the opposite shoulder and upper limb are brought forward. In this subphase, the opposite limb is still in contact with the support, i.e. in a period of double support. Plantar flexion at the ankle joint and pronation of the foot, synchronised with flexion at the knee joint, cause a relative shortening of the supporting limb (Popov 2009). Thanks to this, the COM is not pushed up sharply but is shifted evenly and minimally, with a smooth sinusoidal movement forward (Fig. 2).

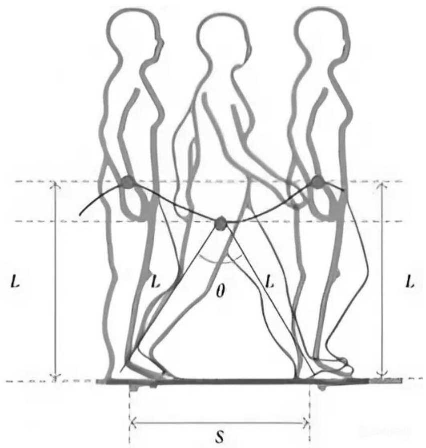



**Figure 2.** The sinusoidal trajectory of the centre of mass.

After the initial contact, the foot descends into plantar flexion, simultaneously moving the lower leg forward, causing contact with the entire plantar fascia of the foot (sole). While in contact with the sole, the supporting leg is ready to bear the entire body's weight. The hip joint begins to extend, causing a gradual displacement of the trunk forward. At the end of this subphase, the contralateral limb is detached from the support and starts transitioning to a single support period. Only the supporting limb bears the body's entire weight during the mid-stance phase. This phase begins when the opposite limb separates from the support and continues until the COM moves in front of the supporting limb and its heel begins to detach from the support. In the ankle joint, gradual dorsiflexion occurs under gravity, pushing the lower leg forward. The knee joint is in slight flexion, and as a result of this flexion moment, the extensors of the knee joint are activated. The abductors in the hip joint neutralise the action of gravity, tilting the pelvis towards the swing limb. The body and shoulder girdle are neutral and rotate toward the swing limb. With the separation of the heel from the support, the penultimate subphase of the stance phase begins and ends with the initial contact of the opposite limb and the restoration of double support. Throughout this subphase, the COM is in front of the supporting limb, and the body "staggers" forward under the influence of gravity. During the last subphase, the fingers of the supporting limb detach from the support as the push-off is completed by the flexors of the thumb, which remains the last in contact with the support, and the body's weight moves to the opposite limb. The so-called pre-swing subphase occurs, thus initiating hip and knee joint flexion.

The second phase of the gait cycle is the swing phase, divided into three subphases – initial, middle, and terminal swing. This phase begins when the thumb of the lower limb is attached to the support. During the initial subphase, the swing limb is behind the body and must be brought forward. The ankle dorsiflexors extend the foot. Thus, the simultaneous flexion in the hip and knee joint and the dorsiflexion in the ankle joint contribute to the relative shortening of the limb, which can move forward without hindrance. During mid-swing, the dorsiflexors hold the foot in a neutral position. Flexion in the hip joint gradually moves the swing limb in front of the body, and the lower leg stands vertically on the support. During the terminal swing, the ankle dorsiflexors remain active and hold the foot in a neutral position, preparing it to do the heel strike.

The movements of the lower limbs when walking are carried out in synchronisation with the movements of the trunk and upper limbs, which, although not so decisive, contribute significantly to the smoothness and economy of the gait. When walking, the COM is not only displaced forward but also deviates in vertical and lateral directions, and the pelvis is displaced in the frontal plane, making a slight depression towards the swing limb. When walking, the pelvis also rotates in the transverse plane (Fig. 3). The rotation is most pronounced during the heel strike, with the pelvis rotated forward towards the swing limb and reciprocally backwards towards the support limb. This movement begins at the pre-swing subphase and continues throughout the swing phase. The rotation of the pelvis and the divergent position of the lower limbs create a rotational inertia towards the side of the posterior (support) limb. This moment of inertia is neutralised by the shoulder girdle's counterbalanced rotation and the upper limbs' counterbalanced movements (Popov 2009; Mirelman et al. 2018; Northeast et al. 2018)

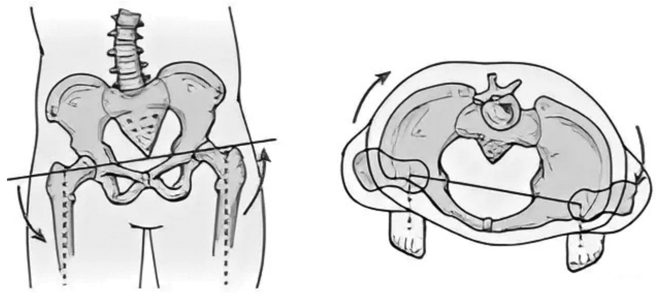


**Figure 3.** The depression and rotation in the pelvis during walking.

## Gait parameters

The main characteristics for determining gait parameters are divided into two groups: spatial and temporal. Spatio-temporal indicators provide basic information about the quantitative characteristics of the gait (Popov 2009). The normal values of these indicators vary according to the person's age, sex, height, length and shape of the limbs, distribution of mass in the body, joint mobility, muscle strength, type of clothing and shoes, load carrying, motor habits, and psychological status.

### 1. Spatial characteristics

According to Rigas (1984), normal gait has the following spatial indicators: stride length, step length (1/2 step), stride width, and foot angle. The ichnography method is used to study the spatial indicators of gait (Senden et al. 2009).

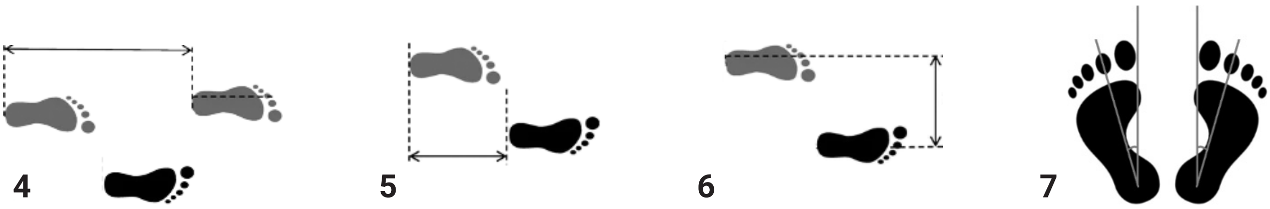
Stride length varies between people (Fig. 4). It depends on the length of the lower limbs, the body's total height, gender, age, and other factors (Cameron and

Monroe 2007). With age, stride length typically decreases. As walking speed increases, stride length increases. Each stride consists of two steps – left and right.

Step length measures the distance between the two feet when both limbs are in contact with the support (Fig. 5). There is always a minimal difference between the left and right steps, but practically, they are considered equal. Comparing the length between the left and right steps is an indicator of the symmetry of the gait (Ziegler et al. 2024).

The step width is measured as the lateral distance between the centres of the two heels when they are in support (Macellari et al. 1999). Ichnographically, it is determined by the line that is perpendicular to the main line in the direction of walking (Fig. 6). It is measured between the end of the footprint of the right and left foot (Brandes M. et al. 2006).

The foot angle is measured between the longitudinal axis of forward displacement of the body and the line connecting the center of the heel with the second toe (Inai et al. 2023). It is determined by the angle formed by the axis of the footprint and the straight line of the walking direction (Fig. 6).




**Figures 4–7. 4** Stride length; **5** step length; **6** step width; **7** foot angle.

### 2. Temporal characteristics

They include the stance and swing phases, cadence, stride and step time, single and double support time and speed.

The stance phase considers the duration of contact of one limb with the support surface (Li et al. 2010), and the swing phase is the period during which the corresponding lower limb is not in contact with the support.

The temporal characteristics also include considering the time required to complete one stride and, respectively, one step. Stride duration is measured between the two consecutive contacts of the same limb with the support.

The cadence reflects the number of steps per unit of time. Cadence = number of steps/min. The more the cadence increases, the more the double support duration is reduced (López-Nava et al. 2016).

Speed reflects the linear displacement of the body per unit of time. Speed of movement = distance travelled/ unit of time. A reading in centimetres/second, meters/minute, or kilometres/hour is usually used.

## Kinetics of walking

Kinetics is concerned with analysing the action of internal and external forces acting on the body during walking.

The external forces acting on the body are inertia, gravity, and support reaction. Inertia arises from the moments of inertia created by the acceleration of the body's individual parts. The force of gravity always acts vertically downwards. The reaction of the support arises from the counteraction of the supporting surface (Newton's third law), i.e. it is the opposite of the forces caused by moments of inertia and gravity.

The muscle action carries out the internal forces during walking, and the capsule-ligament and tendon structures help to neutralise and absorb the external forces. Muscle activity provides the necessary motor, neutralising or controlling action while maintaining the vertical posture of the body and locomotion.

## Methods for measuring gait parameters

Human gait analysis has been the subject of numerous research methods in recent years. Researchers are focused on achieving quantitative and objective measurements of the various parameters of the gait, with the aim of application in various fields of science – most often in sports and medical practice, but also for identifying persons in forensics. Focusing on the medical aspect, changes in gait reveal key information about people's quality of life (Muro-de-la-Herran et al. 2014). This is of particular interest in the study and analysis of information on the development of various diseases, such as neurological and traumatic conditions impairing locomotor activity, as well as systemic diseases and degenerative diseases caused by ageing that affect a large percentage of the population. The accurate and objective analysis of gait parameters and their tracking and evaluation over time allow for early diagnosis of diseases and prevention of complications and help to choose the best therapeutic approach.

Muro de la Herran et al. (2014) describe the types of gait research methods, analysing their advantages and disadvantages in depth when applied to different research purposes.

Traditional methods used to determine gait in clinical conditions are semi-subjective. Based on observation, a specialist determines a patient's type of gait. Practical recording of the spatial parameters of the gait is done by measuring a given distance (5 or 10 m) on the terrain (floor/support surface) and marking the steps. Then, the length of a stride, a step, and the number of steps for the specified distance (Fig. 8) are measured. A stopwatch is used to register the time characteristics, which counts the time to pass for a given distance (Fig. 9).

8

9

**Figures 8, 9. 8** Tape measure; **9** stopwatch.

According to the formula (the path "S" is equal to the speed "V" multiplied by the time "t" – S = V × t). The rest of the spatio-temporal characteristics of the gait are calculated. In many cases, this is also associated with taking surveys in which the patient is asked to give a subjective assessment of the quality of his gait. A disadvantage of these methods is the lack of precision, which has a negative effect on the conclusions and treatment of the various pathological conditions.

In recent years, the advancement of new technologies has led to the creation of technical devices that allow the objective assessment of the various gait parameters. Using such devices leads to a significantly more efficient measurement of the gait parameters and provides specialists in this field with a larger amount and more reliable information (Favela et al. 2010). Devices for studying and analysing e human gait can be divided into two main groups: non-wearable and wearable sensors. Hybrid systems are also known as a third group, which combine the two methods. Several studies prove the validity of the abovementioned methods for research and analysis of gait parameters.

## 1. Non-wearable sensors (NSW)

These require controlled research facilities with sensors installed to capture gait data. The subject evaluated moves along a pre-marked path (Zijlstra 2004) and can be classified into two subgroups: based on image processing (IP) and based on floor sensors (FS). IP systems are formed by several digital or analogue cameras with object-glass, which, through one or more optical sensors, capture data about the subject's gait and make objective measurements of the various parameters through digital image processing (Zijlstra and Hof 2003). Analogue or digital cameras are the most commonly used devices. Other types of optical sensors are used, such as laser scanners (LRS), time-of-flight (ToF) sensors, structured light scanners, infrared thermography and stereoscopy. FS systems are placed on the floor on so-called "force platforms", where gait information is measured by pressure sensors, ground reaction force (GRF) sensors, and transducers that convert energy from one form to another (Kotiadis et al. 2010) by measuring the force exerted by the subject's lower limbs on the floor while moving (Fig. 10).

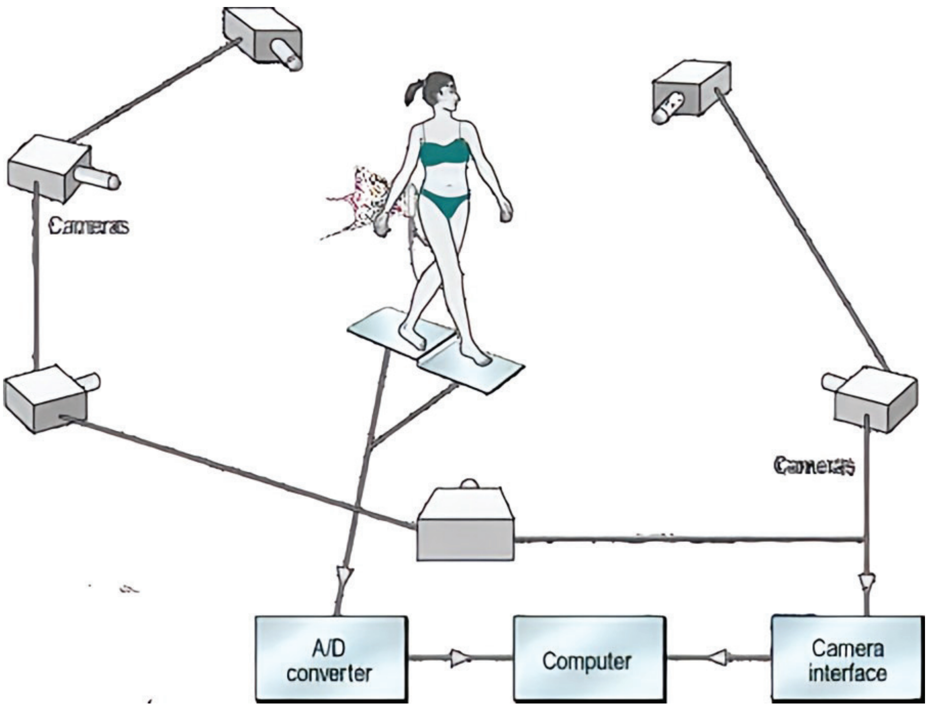



**Figure 10.** Non-wearable sensors.

## 2. Wearable sensors (WS)

They allow data to be analysed outside laboratory conditions and to capture information about gait parameters during daily human activities (Rueterbories et al. 2010). WS systems use sensors on different body parts, such as feet, legs, knees, hips or lower back (Gonzalez et al. 2009). Different types of sensors are used to capture the signals that characterise human gait (Godfrey et al. 2008). These include force and pressure sensors, accelerometers, gyro sensors, magnetometers, extensometers, goniometers, ultrasound sensors, active markers, electromyography, and more. Force and pressure sensors measure the stance response that occurs during the stance phase in the gait cycle through electrodes that proportionally convert the measured pressure. The most widely used models are capacitive, piezoelectric, and piezoresistive sensors. Inertial sensors are electronic devices that measure and report the velocity, acceleration, and gravitational forces of an object using a combination of accelerometers, gyroscopes, and sometimes magnetometers (Schwesig et al. 2011). The accelerometer measures the acceleration of moving objects. A gyroscope is a device used to measure or maintain orientation and angular velocity (Lau and Tong 2008). Calculating acceleration and angular velocity is possible with a combined three-axis accelerometer and a three-axis gyroscope (Saremi et al. 2006). Analysis of the accelerometer signals through different algorithms allows the extraction of information about the number of steps taken in a certain period, along with other gait characteristics (Auvinet et al. 2002). Inertial sensors are one of the most widely used systems for gait research and analysis (Fig. 11). Goniometers are mainly used to study the angles of the hips, knees, ankles and metatarsal joints. Strain gauge-based goniometers work with a resistance that changes depending on how much the sensor is bent. Ultrasonic sensors are mainly used to obtain data on the spatial parameters of gait, such as stride length and width. Knowing the speed at which sound travels in air, ultrasonic sensors measure the time that takes for the ultrasonic waves to be sent and received. Electromyography studies the electrical activity of nerves and muscles. They use electrical stimulation along the course of the given nerve and the level of its involvement, or the presence of muscle damage is determined. Performing EMG is used to diagnose neuropathies, multiple sclerosis, paresis of the foot as a result of disc herniation, etc.

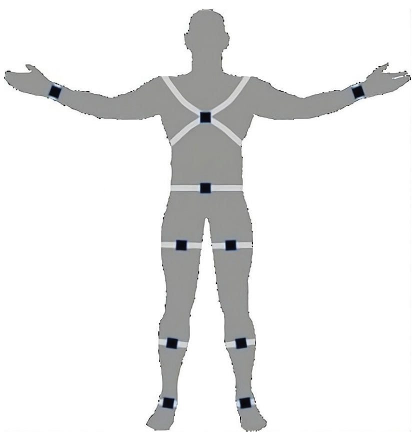


**Figure 11.** Wearable sensors.

In this context, we conducted a research project to study gait parameters for monitoring the recovery of locomotor activity in patients following lower limb injuries. This involved examining the technical features of modern electronic devices used for research and analysis in clinical practice. The marketing reference confirmed the compliance of a wearable technological device, an inertial sensor type, with appropriate software that registers the spatial and temporal gait parameters. The device is a G-WALK model manufactured by BTS “Bioengineering” (Fig. 12). The functional characteristics of the BTS G-WALK are recorded by a wireless sensor (G-Sensor) consisting of 4 inertial platforms, each composed of a triaxial accelerometer, a triaxial magnetometer and a triaxial gyroscope. Positioning the device at the L2 – S1 vertebra level allows objective functional analysis of various movements (e.g., walking, jumping, running). Thanks to Fusion Sensor technology, the system is more accurate and sensitive. The device transfers the data to specialised software and calculates all the parameters necessary to give an assessment, which makes it possible to determine a training strategy or rehabilitation treatment. The BTS G-WALK is an easy-to-use device that can provide accurate, objective and quantitative data. The tests are performed quickly and do not require preliminary preparation by specialists. Automatic report generation makes BTS G-WALK the ideal solution for a wide range of clinical and other research applications. BTS G-WALK enables the following tests to be performed and information to be obtained: spatiotemporal gait parameters (general kinematic characteristics, left and right limb symmetry index, stride symmetry index), pelvic motion index (kinematics of pelvis), “6-minute walking test” (assessment of the functional capacity of the patient, depending on age), “Timed up and go” (TUG) test, “Turn” test, “Free” test, “Run” and “Jumps” tests. The data can be used and analysed in an Excel spreadsheet.

Several working hypotheses were formulated regarding the aim and tasks set for implementation in the research project. It is expected that implementing the precise possibilities for registering the locomotor activity, the following results will be established and analysed: gait recovery time (without the use of aids ) in the different groups of patients after injuries of the lower limbs, as


**Figure 12.** Wearable inertial sensor device – G-WALK.

well as tracking the recovery of the individual parameters of the gait according to spatial and temporal characteristics; functional recovery of gait in patients after traumatic conditions of the hip joint, functional recovery after soft tissue injuries of the knee joint and post-traumatic conditions of the ankle joint; the duration of gait recovery in patients with complex regional pain syndrome after injury in the ankle joint; the severity of the injury and its importance for making an appropriate complex rehabilitation program; does gender and age matter for functional recovery of gait after lower extremity trauma; the existence of significant medico-social problems in elderly patients, associated with worsening of the quality of life, as a result of impaired locomotor activity.

## Conclusion

From the reviewed literature, it was found that there are not many studies that indicate data from pathological gaits research and, in particular, those of post-traumatic conditions, in which the use of aids (two axillary crutches) is necessary. The data about comparative analysis of the different gait parameters in lower extremity injuries were insufficient. No definite information was found on the time required for functional recovery of locomotion in patients after lower extremity trauma in the area of individual joints (hip, knee and ankle). Single articles have indicated the recovery of gait parameters in a specific injury, yet not providing comparative data with other traumatic injuries. Data on the recovery of gait parameters after lower extremity trauma in different age groups are also scarce, as in the gender differences. No data were found on the necessary period of recovery of normal gait with complex regional pain syndrome complication and a comparative analysis with patients without such a complication. These currently unspecified questions related to the recovery of gait parameters during locomotor activity after lower extremity trauma motivated us to carry out the present review.

## Additional information

### Conflict of interest

The authors have declared that no competing interests exist.

### Ethical statements

The authors declared that no clinical trials were used in the present study.
The authors declared that no experiments on humans or human tissues were performed for the present study.
The authors declared that no informed consent was obtained from the humans, donors or donors' representatives participating in the study.
The authors declared that no experiments on animals were performed for the present study.
The authors declared that no commercially available immortalised human and animal cell lines were used in the present study.

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This study was funded by Medical University– Pleven under research project No.5/2023. There are insured aids to assist walking, devices, materials and consumables for registering gait parameters and analysing the recovery of locomotor activity in patients with lower limb injuries.

### Author contributions

Atanas Drumev conducted the examinations and study of the patients. Danelina Vacheva structured the manuscript and conducted the analysis. Both authors contributed to the writing and revision of the manuscript.

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### Data availability

All of the data that support the findings of this study are available in the main text.

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