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Biomechanics of Gait: Engineering Solutions for Rehabilitation

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ABSTRACT

Human locomotion is a complex interplay between muscles, bones, joints, and neural controls. Understanding gait biomechanics has profound implications for engineering solutions aimed at rehabilitation. This paper examines the intricate mechanics of human gait, including phases of walking, the role of ground reaction forces, and the influence of kinematics and kinetics. It highlights common gait abnormalities, methods for gait assessment, and the importance of developing assistive technologies like robotic exoskeletons and virtual reality-based therapies. Rehabilitation engineering bridges the gap between clinical needs and biomechanical understanding, leading to innovative therapies that restore mobility and improve quality of life. Future research directions propose integrating personalized digital rehabilitation, gamification, and advanced sensor technologies to address emerging challenges in gait dysfunction and enhance recovery outcomes. By combining biomechanical insights with engineering ingenuity, the path forward promises transformative impacts in restoring and enhancing human mobility.
Keywords: Biomechanics of Gait, Gait Rehabilitation, Locomotion Analysis, Wearable Sensors, Ground Reaction Forces, Rehabilitation Engineering.

INTRODUCTION

Engineering solutions for rehabilitation to restore locomotion have been analyzed in this article. The focus is on the biomechanical analysis of gait. The forces that human beings apply to the environment via contact during locomotion can be measured through wearable sensors or attached instruments and are used to recover the locomotion inputs into the computer. The locomotion controller can either enhance existing healthy gait or mechanically mimic pathological gait. Methods of human locomotion control captured from the model library can be applied to the control of individuals with motor impairment through rehabilitation robots. The biomechanics and motor control of human gait have been studied. The human body is a complex system involving many interacting muscles, bones, and joints. Understanding the mechanics of gait, including the high-dimensional inputs that can be administered and the wide spectrum of possible outputs, is an important challenge in bioengineering and bio-robotics. It could potentially provide profound knowledge about the motor control strategies that enable the generation of stable, robust, and adaptable locomotion in creatures. Walking has its biomechanic characteristics, and walking models of a rigid trunk are presented in this article. The sliding friction between the moving foot and the ground is modeled as a viscous force that relays the ground's support to the body. Using the balance of ODEs, subtle biomechanical principles on gait generation have been proposed [1, 2].

Understanding Gait Mechanics

Gait refers to how a person walks. Healthy walking is essential as it is the normal mode of transportation, and functional impairment of gait due to injury, disease, or deterioration can drastically reduce the quality of life. Injury can occur in any joint of the body involved in walking, and locally non-pathological joints may become symptomatic due to secondary changes in kinematics and kinetics. Consequently, understanding the basic mechanics of walking, identifying mechanical compensation for dysfunction, and developing rehabilitation/engineering solutions is crucial for many people. Nevertheless, researchers have not reached an adequate understanding of the mechanics of normal or modified gait, and solutions to modify programmed solutions or penalize compensation have not been developed yet. Gait mechanics refers to the mechanical analysis of the actions of "walkers" on ground surfaces and is usually considered "normal" walking at "natural" speed across level ground. Normal walking is quasi-periodic, symmetric, and mass-symmetric, as well as low-dimensional, oscillatory, controlled with feedback, predominantly slow, and without external disturbances. The basic mechanics are formulated in terms of gliding, inertia, axial rotation, and elastic forces. Walkers modulate speed, trochoid characteristics, and gradients, with possible gait bifurcations based on dynamic symmetry or cycled with changing parameters. Mass- and most inertia-asymmetric walking modes or trot dissect speed and trochoid ranges. Simple "biped" and wing-like mechanics are often considered flawed. Gait mechanics is suggested as a control engineer's "data-driven" methodology for the treatment of gait and modifying gait functionality in normal, modified, and pathological gait conditions. Basic mechanics under natural walking are a few forces that act on a simple mass-symmetric machine considered as a point mass, thus generating basic gait modes based on its single degree of freedom related to the laws of universal mechanodynamics. Gait bifurcation, perceived gait representations, and modified gait have been addressed. The closed-loop and feedback control of healthy, modified, and pathological gait styles based on tuning basic mechanics and parameters of active and passive components of the ankle, knees, L5, and HAT leaks are discussed. Potential solutions are elaborated to the incomplete understanding of the mechanics of walking and lateral perturbations as well [3, 4].

Phases of Gait

The human gait is a highly intricate and recurring process that necessitates the coordinated interaction of muscles, bones, and the nervous system. Its primary purpose is to support an upright posture and maintain balance under both static and dynamic conditions. The gait cycle is defined as the duration from the initial contact of one foot to the subsequent occurrence of the same event with the same foot. Ensuring the proper functioning of the locomotion system is essential because malfunctioning lower limbs significantly reduce the autonomy and quality of life of humans. Among these models, the most commonly adopted one consists of two main phases: stance and swing. The gait cycle can be divided into two distinct phases: the stance phase and the swing phase. The stance phase occurs when the foot touches the ground and the leg is supported. It begins with the initial contact (IC) event of the foot with the ground and ends with the toe-off (TO) event, which occurs when the heel of the foot lifts from the floor. The stance phase is the part of the cycle in which the Ground Reaction Forces (GRF) are present. Whereas, the swing phase occurs when the foot does not touch the ground and, thus, the leg oscillates. It begins with the TO event and ends with the next IC event. The extension in the percentage of the cycle of these three periods depends on the walking speed. The GRF is non-null only during the stance phase. For slower walking behaviours, the stance phase lasts about 60% of the gait cycle. For normal-speed and brisk walking, its duration reduces to about 55% and 49%, respectively. During the stance phase, the vertical component of the GRF has a characteristic double-peaked profile. In normal conditions and at a walking speed of about 1.2m/s, the two peaks are in the range of 0.5 to 1.5 body weight (BW). The first peak corresponds to the loading response, where the center of mass is decelerated, while the second peak is related to the toe-off event [5, 6].

Kinematics and Kinetics

Gait cycle through walking is naturally divided into stance and swing phases. 60% of the gait cycle is stance, and 40% is swing. Ground reaction forces (GRF) are primarily applied to the lower limbs during the stance phase of movement. GRF translates all forces of gait input and can be measured using gait analysis tools. Investigating the kinematics of gait using the ground reaction forces will aid in developing better rehabilitation options for patients and injured adults. Kinetics is the influence of forces that produce or change movement in a structure. Kinetics studies determine the system's movement-producing or changing forces through the reaction forces exerted on a terrestrial system. Measurements can maximize function and reduce compensation at the strategic levels of intervention. Kinematics and kinetics can vary depending on the basic gait analysis, gait analysis for the nondominant or injured limb, speeds of gait analysis, and active assistance force of gait analysis. Similar research methods can be used in other health areas to determine the effect of muscle atrophy, neurological diseases, degenerative changes of the spine, urban complications of the foot, etc. This study poses questions regarding the effect of stance width and base of support during gait initiation on early kinematics, dynamic stability, and parameters of gait in older adults. It applies to thorough relations that deserve attention in terms of both the clinical and biomechanical perspectives. It acknowledges the opinions and wishes of the participants, provides data on measurements and results, and clarifies the relevance and usefulness of the study. Neither researchers nor participants have an irrelevant personal or financial relationship that could influence results and conclusions. Data were collected in a laboratory using a standard 3D motion analysis system with passive markers placed on the participant's body. With nine digital cameras, position data were collected at a frequency of 120Hz. Static and dynamic calibration procedures were performed, and marker trajectories were reconstructed and filtered. Marker clouds were rotated and/or translated to bring the sagittal plane of the subject to the movement plane [7, 8].

Common Gait Abnormalities

From bipedal locomotion and running techniques to new rehabilitation devices, robotics, and intelligent design, motion can be a fascinating subject in a wide range of applications. It can be studied from many perspectives, including physics, physiology, and mechanics. Walking is a cyclic motion characterized by a pattern similar to a sine wave, with the center of mass moving up and down during the motion like a pendulum, swinging about the center of gravity (CG) to develop horizontal motion. As with hand-eye coordination, gait is usually viewed from the mobility or stability perspective. Disturbance or unusual body morphologies result in a non-standard gait that may emerge from the use of a prosthesis or orthosis. Often, these newly developed gaits are impeded from moving in a functional pattern because the basic functions of limbs cannot be adequately utilized. As a result, designing an assistive device that can be operated with a gait that falls out of standard and still provides progress is a challenging topic. Various locomotion assistive devices have been proposed to assist with or control falling gait that is considered to be unsafe. These apparatuses are complex and mostly utilized in human-centered operation where the user specifies the command structure of locomotion. A new type of locomotion assistive device is designed based on a method of locomotion trajectory generation by prescribed motion state transition. Even objectively determining the fallout of the standard gait is the focus of only a limited number of studies. Abnormalities can be categorized into two classes: abnormality in the gait that is still close to standard gait but with some constraints, and unexpected combinations of the gait that cannot be considered as gait. The latter class includes the fidgeting type of motion that is common but may not be easily characterized using existing locomotion generation models [9, 10].

Assessment of Gait

Individuals must evaluate their walking patterns, as ease of movement does not always signify capability. Changes in perception, limb function, context, or environment can affect walking techniques, leading to falls or disability. Gait is a specific movement pattern involving two strides, each divided into a stance (ground contact) and swing (off the ground) phase. Walking speed depends on stride length and frequency, with alterations in these parameters suggestive of pathology. The nervous system, consisting of the central and peripheral systems, is vital for locomotor control. The central nervous system (CNS) continually processes signals from the ground and various sensors to maintain the body's center of gravity (COG) above supporting feet; this task becomes challenging as these areas diminish. The foot-lifting mechanism is orchestrated by a control structure that determines optimal joint angles. When signals surpass permissible thresholds in the CNS, gait disorders may arise, characterized by an inability to maintain balance due to neurological or musculoskeletal impairments. A significant social handicap arises for elderly individuals with gait disorders. Stroke, which causes brain-cell death from reduced blood flow, leads to paralysis in extremities and various neurological challenges, such as spasticity and diminished strength. Foot paralysis shifts the COG, raising the risk for hemiplegic gait and falls [11, 12].

Rehabilitation Engineering

An ever-growing number of scientists and engineers working in gait biomechanics have decided to translate their research results into clinical applications. A major field of application is in gait rehabilitation engineering. Rehabilitation engineering refers to engineering solutions for the rehabilitation of patients with movement disorders, either by the restoration of ended body functions or by substitution of these functions by technical devices. Gait rehabilitation engineering solutions are commonly based on robotics and sensory technology, and are used to provide various types of assisted gait training for plasticity, sensorimotor retraining, and functional movement retraining. Artificial gait devices are an emerging type of assistive device that are designed to partially mimic human gait. Engineering solutions for controlling exoskeletons that assist walking beyond the original purpose of mobility rehabilitation were developed. Some systems that have been developed are industrial robots and service robots that can be iteratively programmed through demonstration to assist in person- and environment-bounded tasks by contextually reasoning and situationally acting. HIEG's design goal is to develop a gait assistive device based on small-scale serial robots that can assist human gait to the same level compared to ankle foot orthosis. A gait rehabilitation robot that assists human gait acts like the robot and the human user jointly control the motion of the gait assistive device. Regarding control strategies of gait rehabilitation robots, passive control is considered to allow both the human user and the robot to benefit from their intrinsic dynamics and motion coordination, and is scalable to easily accommodate different robot and human specifications. Assistive body weight-supported robot-aided treadmill training devices are widely developed and employed. Body weight assistive ratio changes due to user gait adaptation do not consider actual gait development during robot treatment. The gait assistive training performance is evaluated by the mean body weight support ratio during stride evaluation based on the determined support and weighting functions [13, 14].

Therapeutic Approaches

Apart from the engineering-based therapeutic devices, many procedures and devices do not need explicit designs to support gait rehabilitation. The development of a complete understanding of human gait mechanics has led to the development of various engineering solutions that support gait rehabilitation. Most of the devices built in biomedical engineering laboratories comprise simple motors, sensors, and control technologies to remove the biomechanical and physical challenges during the rehabilitation of gait for humans. As a conventional method, educational sessions are also performed with children diagnosed with CP. The engaging and interactive videos and texts about gait and locomotion sequences are shown to children. Compared to video games, these educational materials do not have clear combinations of catch goals, fun, and reward mechanisms, which so far have not been widely practiced in formal settings. Most of them also lack online feedback, demographically-adaptive feedback, although some approaches have emotional stimulus in long-term training. Children diagnosed with CP after the age of six usually suffer from residual gait disorders. Being aware of such disorders would be helpful for their rehabilitation. With the intent of elucidating the abnormal cheese-like gait patterns, the emotional cartoon video clips presenting cognitive dissonance (unexpected exaggeration of gait patterns) were prepared. This 10-minute educational simulation was shown to children in a week-long training class. As a result, most children born with a wide range of gait disorders showed improved understanding of their tasks. They drew their unusual patterns and underwent the self-development of educational materials to help their siblings understand the cheese-like gait features. The reuse of the self-made educational videos was also suggested. After the text and sound editing, the videos can be presented in a class of both healthy and CP children. Recently, virtual reality technology, which has been developed and applied in clinical psychology, was found to be useful for the rehabilitation of patients with spatial neglect following stroke or brain lesion. VR-based therapy provides a safe and effective way to present appropriate stimuli to the patient throughout the rehabilitative process. To incorporate VR technology in current gait rehabilitation devices, DVNET (DV) was built as a therapeutic agent. Unlike commercial VR systems designed for entertainment, this apparatus consists of an actuator that applies biomechanical forces associated with the VR game. By adjusting the suggested environment and personalizing the biomechanical perturbations, engaging and adaptive training will be provided [15, 16].

Technology In Gait Rehabilitation

The most common medical conditions that impair human mobility include stroke, multiple sclerosis, Parkinson's disease, Traumatic Brain Injury, traumatic spinal cord injury, hereditary spastic paraplegia, and transverse myelitis. Regaining functional gait after pathology is an absolute must for independent living, and to achieve this, many neuro-rehabilitation protocols or techniques are offered. Despite the complexity of the pathology and of the locomotor system itself, the rehabilitation of gait predominantly relies on repetitions of the gait cycle: stance and swing, that is, foot and ground interactions. The community of movement science professionals, neurologists, physiatrists, physiotherapists, engineers, biomechanists, kinesiologists, roboticists, psychologists, and educators, are invited to recalibrate this one-sided view of rehabilitation procedures by promoting whole-body movement training as an integrative approach for gait rehabilitation, one in which the simplicity of the explanations for complex movements has to meet the complexity of the movements observed in real life situations. Gait rehabilitation technology, including robots, sophisticated simulators, or careful setups of patterns for patients to follow, is growing exponentially. The reason is simple. Half of the people presenting difficulties in physical functioning have a gait disability. The global population is ageing and chronic conditions, but also accidents, generate more gait impairments and gait-related disabilities that reduce the individuals' ability to perform activities of daily living and to participate in social life. Central neurological conditions represent, worldwide, the main source of gait-related disabilities. Close to 80% of the age group over 65 years suffers, globally, from an age-related condition. These basic data, supplemented with social estimations, lead to the conclusion that rehabilitation of gait, which is seen as the key feature of personal mobility and social participation, is an imminent necessity for humankind [17, 18].

Future Directions in Gait Research

Exciting future research possibilities in gait analysis relate to trauma and addiction. Lower-extremity injuries are common among athletes, especially chronic knee injuries like ACL tears in sports requiring acceleration and sudden direction changes (e.g., soccer, basketball, volleyball). Understanding psychological factors behind conditions like "burn-out" or "over-training" is also significant. Given that

60% of North Americans consume alcohol, studying the interaction between anxiety medications and gait patterns is imperative. For instance, do anti-anxiety drugs lead to maladaptive gait habits? Does gait variability increase after these medications' effects wear off? Exploring how addiction treatments affect daily movement patterns can lead to critical insights. In rehabilitation, changes to normal movement patterns can hinder health outcomes. Personalized digital rehabilitation approaches for young patients recovering from aggressive surgeries are worth investigating. Additionally, integrating gamification, new-media aesthetics, and gerontology could enhance rehabilitation for older adults with congenital or degenerative diseases. New portable gait metrics recording techniques may provide insights into autism and dementia treatment or prevention. In high-performance sports, collaboration among biomechanists, physiologists, and neuromuscular modelers can develop innovative joint mechanics models. Integrating monitoring devices and reduced-coordinate human body models in sports will facilitate creating "popular science" venues and art installations [19, 20].

Case Studies

The gait assist device for pelvic support in gait rehabilitation was first developed as a portable and lightweight frame to apply impinging gravity force on a waist belt, and then a cable-operated driven device that is rigidly mounted on a wheelchair with a three-dimensional ball joint and applies weight force on a pelvic belt. This cable-driven wheeled device is modified to apply upward, downward, rightward, leftward, counterclockwise, and clockwise moments/torques on three joints of the hip and yaw on the waist for rehabilitation of either stroke or post-stroke patients. This device is shown to be effective for the study of gait adaptation and rehabilitation after perturbations on lower limb joints such as the elbow, knee joint, and hip joint. Experimental studies on treadmill locomotion are performed. Perturbations with zero and five degrees of deviated angle of swing leg and stationary height of treadmill belt help to reveal how a geared joint works to adapt to speed or height perturbation. These results imply that it is possible to use these perturbations on the hip or waist joints to change gamma in the adaptive system such that the stretched height is changed to perturb gah or xh [21, 22].

Ethical Considerations

Robot-assisted gait training systems are gaining significant attention in both rehabilitation and biomechatronics. Many existing gait rehabilitation systems utilize actuators that are powered by motors. Exploiting the flexibility of the system's mechanical structure, a novel gait training system that is based on bungee elastic bandages and a double small flying sketch is designed. This system is new on the market and aims to provide rehabilitation training for disabled people, as well as gait trainers in the physical therapy industry. Safety and rehabilitation effects are the two most important criteria for rehabilitation equipment. A 3D dynamics simulation model was produced to evaluate damping and elastic band parameters, explore the principle of biomechanics, and determine the system's safety and. In rehabilitation practice, controlling gait motions requires supervision from therapists using their hands during training. Instead of controlling each joint actively, the therapist can passively guide the patient's body to follow a preplanned active trajectory. This is called a transmission system, which uses passive joints to ensure the patient can follow a predefined trajectory generated by the actuator. The gait transmission system is designed based on multiple mechanisms, including pulley, 4-bar linkage, and crank systems. The proposed transmission mechanism is based on the principle of 4-bar linkages. To fulfill the defined range of joint motions and desired workspace, size optimization analysis is conducted based on function evaluation metrics, including joint trajectories and motion deviation. This proposed gait training mechanism features safe, user-friendly, low-cost mechanical components. A transmission machine is recommended to test its performance in gait detection, analysis, and passive gait motion generation. Given the flexibility of actuating mechanisms, joint matching of the training apparatus and the human body is not an unreasonable expectation [23, 24].

CONCLUSION

The biomechanics of human gait provides essential insights into the complex dynamics of locomotion, which are critical for developing effective rehabilitation strategies. Through a detailed understanding of gait phases, kinematics, kinetics, and common abnormalities, researchers and engineers have created innovative assistive technologies, such as robotic exoskeletons and VR-based rehabilitation systems, that are transforming clinical practices. Gait rehabilitation engineering has evolved from basic support systems to sophisticated, adaptive devices that mimic natural movements and promote neuroplasticity. However, the journey is far from complete. Future directions emphasize the need for personalized, sensor-driven rehabilitation, integration of gamified and immersive therapies, and exploration of gait-related psychological and neurological factors. A collaborative, interdisciplinary approach will be vital in pushing the boundaries of what rehabilitation engineering can achieve, ultimately ensuring better functional outcomes and quality of life for individuals with gait impairments.

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