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ORIGINAL ARTICLE

A novel gait-based synthesis procedure for the design of 4-bar exoskeleton with natural trajectories

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Abstract *Background/Objective:* Human walking involves the coordination of brain, nerves, and muscles. A disturbance in their coordination may result in gait disorder. The gait disorder may be treated through manually assisted gait training or with the aid of assistive devices/robotic devices. These robotic devices involve mechanisms which are synthesized using complex conventional procedures. Therefore, in this study, a new gait-based synthesis procedure is proposed, which simplifies the mechanism synthesis and helps to develop a mechanism which can be used in rehabilitation devices, bipeds, etc.
Methods: This article presents a novel procedure for the synthesis of 4-bar linkage using the natural gait trajectories. As opposed to the conventional synthesis procedures, in this procedure, a global reference frame is considered, which allows the use of hip trajectory while moving. Moreover, this method is divided into two stages, and five precision points are considered on the hip trajectory in each stage. In the first stage, the 4-bar linkage is designed, thereafter, the configurations of the linkage for the remaining precision points are determined in the second stage. The proposed synthesis procedure reduces the complexity involved in the synthesis and helps in the simplification of the problem formulation. A two-stage optimization problem is formulated for minimizing the error between the generated and desired hip trajectories. Two nature-inspired algorithms are used for solving the optimization problem. The obtained best results are presented, and the designed linkage is simulated in MATLAB.
Results: The best design of the linkage is obtained using particle swarm optimization. The trajectories generated by the designed linkage using the proposed methodology can accurately track the desired path, which indicates that designed linkage can achieve all the orientations required during walking. The positions of a whole lower limb at all the desired precision points are demonstrated by stick diagram for one gait.
Conclusion: The proposed methodology has reduced the complexity of synthesis procedures and used optimization techniques to obtain a feasible design of the mechanism. The stick

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diagram of the designed mechanism obtained using the proposed method indicates that the designed mechanism can walk smoothly. Hence, the designed mechanism can be used in the rehabilitation devices. Furthermore, a conceptual design of an exoskeleton knee is also presented.

The Translational Potential of this Article: Many hospitals and individuals have used the immobile and portable rehabilitation devices. These devices involve mechanisms, and the design of mechanism plays a vital role in the functioning of these devices; therefore, we have developed a new synthesis procedure for the design of the mechanism. Besides synthesis procedure, a mechanism is developed that can be used in the rehabilitation devices, bipeds, exoskeletons, etc., to benefit the society.

Introduction

Human walking is a complicated and rhythmic kinematic movement which involves the coordination of brain, nerves, and muscles. A disturbance in their coordination may result in gait disorder [1]. Typically, it is found among elderly patients who have amputated limbs, musculoskeletal disorders, spinal cord injury, etc. These patients may be treated by manually assisted gait training or with the aid of assistive devices. The manually assisted gait training has various drawbacks such as the long training duration and its frequency of the training. It is also dependent on the availability of the therapist. Moreover, it is backbreaking and physically demanding for the therapists, and lacks repeatability [2,3].

In contrast, robot-assisted gait training (i.e. assistive device) can be used to increase the duration and number of sessions for training. In addition, it limits the requirement of the number of therapists per patient [4]. These assistive devices may be used to overcome the limitations of manually assisted gait training [5]. Various gait rehabilitation devices have been developed over the years such as Lokomat [3], ReoAmbulator [6], LOPES [7], ALEX [8], linkage mechanism for gait rehabilitation [2], and UCI gait mechanism [9]. However, these devices are meant for patients at hospitals and rehabilitation centres as they provide training in the confined areas, and patients do not feel the realistic experience of walking. Alternatively, portable wearable robots are required, which can be used at home. Various portable rehabilitation devices have been developed, for example, eLEGS [10], compact portable Knee—Ankle—Foot robot [4], and ReWalk [11]. These devices may be used to assist patients in standing and walking. However, these exoskeletons are battery operated, and some of them require crutches for balance [12,13]. In addition, they use a single-axis, revolute joint at the knee, which allows only rotational motion. Therefore, to select the best mechanism, it is vital to comprehend the biomechanics of the knee joint and its coordination with the hip and ankle joints.

The anatomy of knee joint varies with age, whereas its complex function remains constant. The knee joint is also referred as a gliding hinge joint. It offers six-degree of freedom range of motion, which involves three rotational and three translational movements. Flexion—extension, internal—external, and varus-valgus movements come under rotation, whereas anterior-posterior, medial-lateral, and compression—distraction movements come under translation [14]. The experimental trials of the rehabilitation devices such as Lokomat clarify the fact that ankle trajectory can be considered as planar in sagittal plane [2,3]. Rolling and gliding are the key motions of the knee joint in the sagittal plane. Also, they are considered as the basic mechanism of movement between femur and tibia as shown in Figure 1. This kinematic motion of the knee joint can be achieved through cross 4-bar linkage where anterior cruciate and posterior cruciate ligaments can be considered as rigid links [15,16]. The 4-bar linkage allows the combination of rotation and translation motion of the knee joint in sagittal plane [17]. Also, it has been used for the knee joint of bipedal robots [17—20] and prosthetic knee joints [21]; therefore, to imitate the complex function of the knee joint for creating orthotic and rehabilitation devices, a 4-bar mechanism can be used.

Various gait rehabilitation devices and exoskeletons are available, in which different mechanisms have been used for the knee, ankle, and hip joints. Recently, a linkage design gait trainer (LGT) has been developed which used a 4-bar linkage mechanism to generate normal gait trajectories. It combines a commercially available walker with linkage system which makes the LGT device complex [22]. A revolute joint is typically used at the knee in the portable active orthotic device [23]. However, it does not imitate the complex

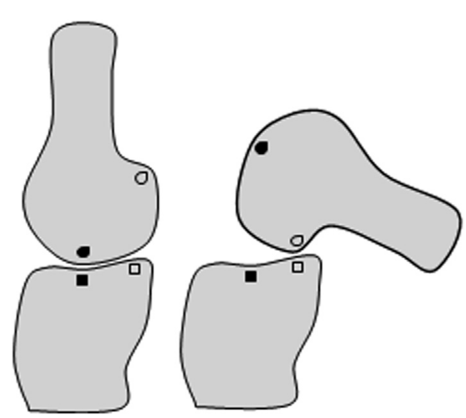

Figure 1 Contact points generated while rolling and gliding motion, when femur moves relative to tibia.