TRANSFERRING ELEMENTARY CHARACTERISTICS OF HUMAN GAIT TO MOBILE ROBOTIC GAIT REHABILITATION SYSTEM

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ABSTRACT

Rehabilitation exoskeletons are becoming important elements of gait rehabilitation after spinal cord injury, neurological injury or traumatic brain injury. Current designs assume relatively confined movement that is almost exclusively in domain of sagittal plane. However, human gait is three dimensional movement that requires synchronized control of cyclical leg movement and forward progression in sagittal plane, weight transfer in frontal plane and turning in transversal plane. Therefore, rehabilitation exoskeletons inevitably impose kinematic constraints than prohibit training of more challenging movement maneuvers such as weight transfer or turning. We suggest novel mobile robotic gait rehabilitation system that tries to bridge this gap and offer complete three dimensional gait training. To optimize configuration of such system we reviewed kinematics of human movement in sagittal, frontal and transversal planes in terms of elementary walking mechanisms and identified those degrees of freedom that contribute most. Integrating these degrees of freedom suggest that such system aims at cognitively more fit subjects that have the capacity to deliver basic gait function but require further training to improve weight transfer, turning or balance.

KEY WORDS

Exoskeleton, rehabilitation exoskeleton, sagittal plane, frontal plane, transversal plane, neurological damage.

1. Introduction

The ongoing progress in the field of robotics in recent years delivered mechanisms that integrate human body and robot into a single functional unit. A particular interest has been raised in the field of gait rehabilitation where significant application potentials of wearable robotic leg exoskeletons have been envisaged [1,2,3]. The main goal of rehabilitation exoskeleton is to facilitate the restoration of the user's gait function after spinal cord injury, neurological injury or traumatic brain injury.

Current state-of-the-art rehabilitation exoskeletons focus on strategies that recognize motor skill of particular individual and provide assist-as-needed rehabilitation [4]. Significantly limited, unreliable and uncoordinated user's input as a result of neurological deficits make this task very challenging. It is domain of rehabilitation exoskeleton to provide intelligent algorithms that are first able to recognize voluntary motor input of particular individual based on recorded joint angle trajectories and monitoring forces and then provide complementary movement actions that stimulate fall safe gait rehabilitation. Control challenges associated with rehabilitation exoskeletons dictate very conservative design. They generally integrate body weight support mechanism for fall prevention and only several actuated degrees of freedom (most commonly hip flexion/extension and knee flexion/extension) and keeping the remaining degrees of freedom rigid (hip ab/adduction, hip int/external rotation) or passive (ankle plantar/dorsi flexion), thus restricting the movement only to sagittal plane that is primarily associated with forward progression. The benefit of such simplified configuration is confined mobility that allows focusing on restoring proper muscle control associated with forward progression rather than immediately attempting to completely restore gait function in all planes movements which would be represent an overwhelming challenge for the patient early after neurological damage. It is advised that only after leg movement is restored to satisfactory level, more challenging maneuvers associated with also movements in frontal (weight transfer, balance) and transversal (turning, balance) planes should be integrated into gait training. At this more demanding stage of gait rehabilitation simplified configuration on the other hand rigorously constrains the movement which very likely hinders expected rehabilitation progress. However fully actuated and compliant configuration that could fulfill the requirements of human movement would be associated also with tremendous control challenges. Nevertheless, encouraged with promising clinical evaluation studies [3,5,6] robotic community is determined to negotiate between the number of active and passive degrees of freedom in order to reach a compromising solution in terms of technical feasibility and rehabilitation goals. Until proper technical solutions are available gait training must inevitably transfer to therapist assisted over ground gait training. Compared to rehabilitation exoskeletons therapist assisted gait rehabilitation is physically intense, very often requires presence of more than one therapist

and may be time consuming. Additionally, given the increasing incidence of neurological disease therapist assisted gait rehabilitation will eventually become less accessible to wider population needing extensive gait therapy.

In this paper we review normal gait kinematics in sagittal, frontal and transversal planes of movement in terms of elementary walking mechanisms to conclude on key configuration requirements for rehabilitation exoskeleton that would enable three dimensional rehabilitation of gait. Results of the analysis were taken into account when conceptualizing novel mobile robotic gait rehabilitation system.

2. Kinematics of Human Walking

Primary goal of walking is to move between two points in three dimensional environment. The path is rarely straight – it is composed of straight and curved sections that demand three dimensional maneuvering which is subject to well synchronized muscle activities of all muscle groups and intact neural control. In addition, humans tend to exploit kinematic redundancy of lower extremities to produce smooth, agile and energy efficient walking. On the other hand, kinematic redundancy of lower extremities leads to substantial challenges when designing rehabilitation exoskeleton. Namely, for rehabilitation exoskeleton to completely obey the feasible range of movement of all degrees of freedom in lower extremities would ideally want to integrate the same degrees of freedom. This would lead to substantial design and control challenges in robotic mechanisms. Instead, when considering the design and the control of rehabilitation exoskeletons a compromise must be reached between technically feasible solution and kinematic complexity that would enable implementation of key walking mechanisms: i) cyclical leg movement and forward progression ii) weight transfer iii) turning and iv) dynamic balance. Experiences from the field of biomechanics show
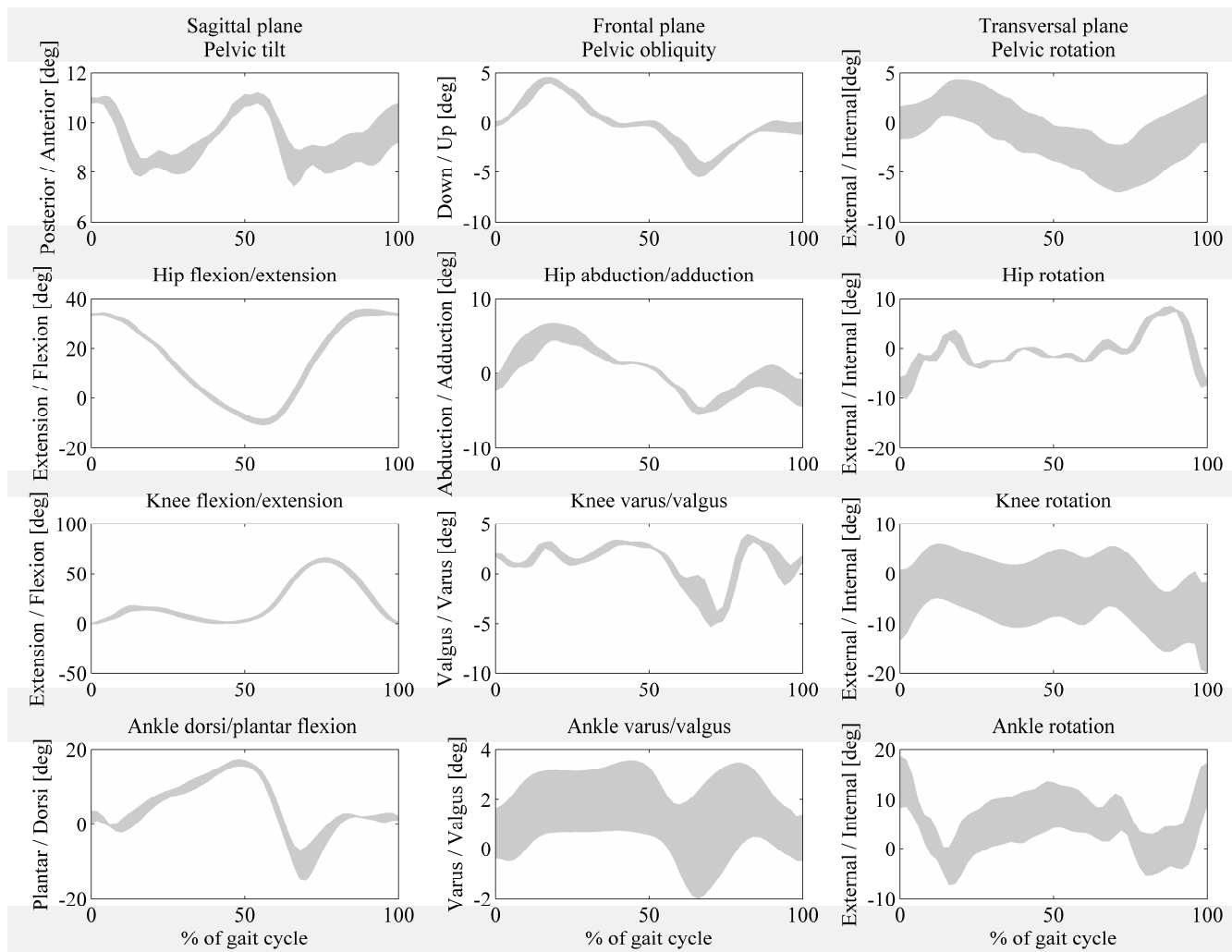

Figure 1. Gait kinematics in normal gait.

that not all degrees of freedom contribute equally to gait. Therefore a reasonable compromising solution would only need to consider degrees of freedom that contribute significantly to elementary gait mechanisms. For this purpose we focus on kinematical analysis of human walking and study human movement separately for sagittal (associated with cyclical leg movement and forward progression), frontal (associated with weight transfer) and transversal (associated with turning) planes of motion by observing movement in pelvis, hip, knee and ankle joint (Figure 1).

Movement in sagittal plane is associated with cyclical leg movement and forward progression. At the time of contact (0% of gait cycle) stance leg is positioned anteriorly with respect to pelvis. We therefore record 40 degrees flexion in the hip, knee is fully extended and ankle close to neutral position prepared for heel contact. Continuing with weight acceptance the stance leg prevents excessive loading and energy losses and conserving the majority of forward momentum. To do so pelvis assumes slightly less anterior position, hip joint first remains at approximately 35 degrees before starting to extend, knee flexion gradually increases until it reaches 20 degrees and loading the heel forces short term ankle movement toward plantar flexion until the foot touches the ground. After passing the vertical in the midstance the stance leg gradually substitutes the energy losses during weight acceptance by extending the hip and the knee joint and eventually by lifting the heel of the ground. Maximum input of energy occurs during push off approximately at the middle of gait cycle when hip and knee joints are at maximal extension and the ankle joint is at maximal dorsal flexion. At the same time the opposite leg touches the ground and the stance leg transfers the weight to the opposite leg and prepares for the swing phase: pelvis leans somewhat more anteriorly, hip joint remains at maximal extension, knee joint starts to flex and the ankle joint rapidly extends from 15 degrees dorsal flexion to 15 degrees plantar flexion. After leaving the ground at approximately 60% of gait cycle people exploit ballistic properties and allow the swing leg to swing as a pendulum without hitting the ground. In the initial swing phase the hip joint resumes with in increasing hip flexion, while approaching the vertical knee joint flexes to a substantial 60 degrees during midswing and the ankle returns to neutral position. In the second half of the swing phase the leg begins preparing for the next contact by swinging the leg forward as much as possible. In terminal swing hip flexion increases to 40 degrees, knee joint extends and ankle remains close to neutral position.

Primary focus of frontal plane movement is to shift the weight according to exchanging support. The range of movement is relatively small due to small step width. At the time of contact both legs are close to vertical in frontal plane. For this reason hip, knee and ankle joints are close to neutral position and pelvis in horizontal position. Weight exchange is initiated by leaning the body towards the new supporting leg – hip adduction increases, knee valgus remains unchanged and ankle moves to valgus and

pelvis tilts up towards stance leg. After hip adduction reaches 10 degrees and ankle approximately 3 degrees of valgus the stance leg starts preparing for the next–hip adduction and ankle valgus decreases to neutral position. In the second half of gait cycle pelvis pattern in frontal plane is reversed. Approximately until the leg lifts of the ground hip abduction rises, so do knee and ankle varus. In the remaining of the swing phase the hip, knee and ankle return to initial positions and prepare for new contact.

Movement in transversal plane is focused on turning. The range of motion depends on the radius of turning. At the beginning of gait cycle pelvis is aligned in neutral position, hip is at 10 degrees external rotation, knee 5 degrees external rotation and ankle at 15 degrees internal rotation. Once pelvic internal rotation starts increasing hip joint and knee joint return toward neutral positions and the ankle adjusts from 15 degrees internal rotation to 5 degrees external rotation. In midstance pelvis begin to realign with neutral position whereas all joints reverse their movement and settle midway with respect to initial position. In the second half of gait cycle pelvic rotation is also reversed whereas the position of hip, knee and ankle joints remains almost unchanged until the midswing when they begin preparing for the new contact. Until the end of swing phase hip external rotation shifts toward 10 degrees, knee internal rotation progressively increases until reaching 10 degrees and ankle rapidly moves to 15 degrees internal rotation.

While all planes are primarily responsible for separate gait mechanisms they are not independent. As already addressed transferring weight to supporting leg in frontal plane of movement is necessary for sufficient foot clearance as well as for forward propulsion. For stable and energy efficient walking therefore requires well coordinated movement in all planes of movement.

3. Application to Mobile Robotic Gait Rehabilitation System

Results of the analysis were taken into account when conceptualizing novel mobile robotic gait rehabilitation system. We also assumed that an exoskeleton is an unstable mechanism that is prone to falling when used by a subject with weak neural motor control. For this reason the design concept assumes three main components: mobile platform, pelvis unit and powered orthosis. Conceptual solution for mobile robotic gait rehabilitation system is schematically presented in Figure 2.

3.1 Mobile Platform

Mobile platform is composed of rigid frame supported by four wheels, each equipped with a steering motor. They have the capacity to deliver omnidirectional mobility to mobile platform. In terms of gait requirements mobile platform provides actuated linear movement in the direction of walking and actuated turning. Degrees of
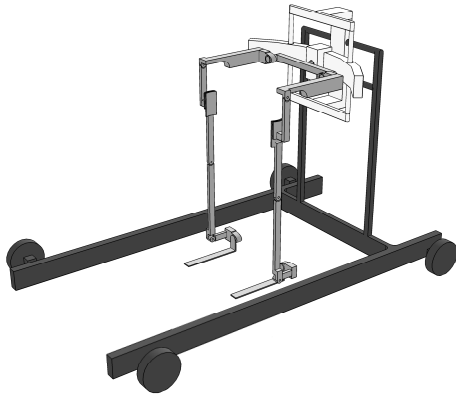
Figure 2. Conceptual solution for mobile robotic gait rehabilitation system: mobile platform (dark gray), pelvis unit (white) and powered orthosis (light gray).

freedom of mobile platform are schematically presented in Figure 3.

3.2 Pelvis Unit

Pelvis unit is composed of two actuated linear units that are positioned perpendicular. One is aligned with vertical and the other is aligned with horizontal and perpendicular with respect to direction of walking. They provide active support for proper weight transfer to the stance leg and compensate body weight if required in a way to deliver active assistance to horizontal and vertical pelvis movement. In addition, vertical unit carries the two successive passive rotational degrees of freedom; first one is designed as semi-circular rail with center axis aligned with longitudinal axis of human body to provide pelvic rotation whereas the second is aligned with medial axis of pelvis and provides pelvic oblique degree of freedom. Degrees of freedom of pelvis unit are schematically presented in Figure 4.
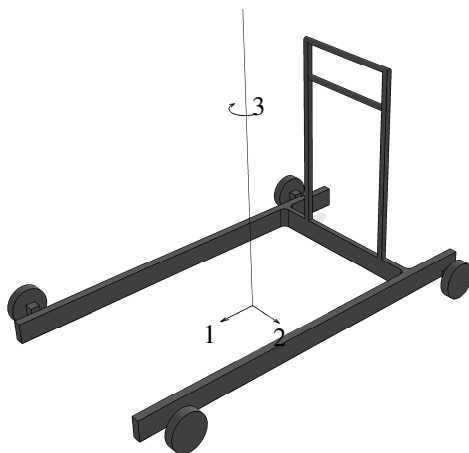

Figure 3. Schematic representation of degrees of freedom of mobile platform: 1 – linear forward/backward, 2 – linear medio/lateral, 3 – rotation
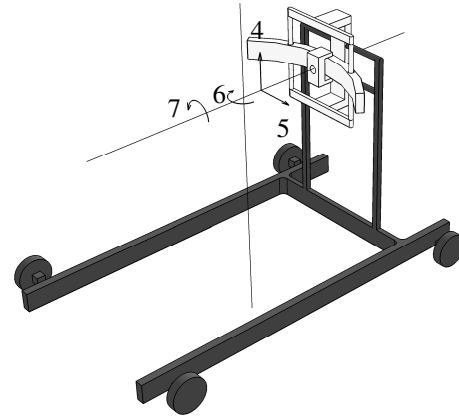

Figure 4. Schematic representation of degrees of freedom of pelvis unit: 4 – pelvis up/down, 5 – pelvis left/right, 6 – pelvis rotation, 7 – pelvis oblique.

3.3 Powered Orthosis

Powered orthosis provides means for direct interaction with pelvis and lower extremities. Configuration of the orthosis is divided into segments connected with rotational degrees of freedom which are aligned with corresponding degrees of freedom of the hip, knee and ankle of the user. Hip joint is a series of three successive rotational degrees of freedom that correspond to hip abduction/adduction, hip flexion/extension and hip external/internal rotation. Hip abduction/adduction assumes passive rotation with passive spring-like element for compensating weight of orthosis leg, hip flexion/extension assumes actuated hinge joint and hip external/internal rotation assumes semi-circular and spring-preloaded passive rail with center axis aligned with longitudinal axis of thigh. Mechanical linkage connecting the three joints can be adjusted in such way to ensure that the intersection of rotation axes of all three degrees of freedom is anatomically aligned with hip joint of the user. Knee joint is considered as a single degree of freedom actuated rotational joint enforcing knee extension/flexion. Ankle joint is composed of two rotational degrees of freedom. The first one is actuated and anatomically aligned with ankle joint so that it enforces ankle plantar/dorsal flexion whereas the second is passive and spring pre-loaded and ensures ankle varus/valgus. Degrees of freedom of powered orthosis are schematically presented in Figure 5. All degrees of freedom as envisaged in mobile robotic gait rehabilitation system are summarized in Table 1.

The presented concept has been used as starting point in the development of rehabilitation platform that is being developed within the project CORBYS [www.corbys.eu]. Complete CAD of CORBYS system is presented in Figure 6.
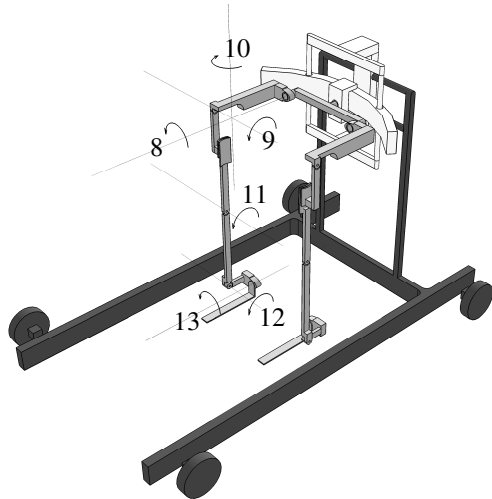
Figure 5. Schematic representation of degrees of freedom of powered orthosis: 8 – hip ab/aduction, 9 – hip flexion/extension, 10 – hip ext/internal rotation, 11 – knee flexion/extension, 12 – ankle dorsal/plantar flexion, 13 ankle. varus/valgus.

4. Conclusion

In this paper we first identified key walking mechanisms and then focused on normal gait kinematics to identify major contributors to gait. The result of analysis showed that gait is combination of movements in sagittal (primarily associated with cyclical leg movement and forward progression), frontal (primarily associated with
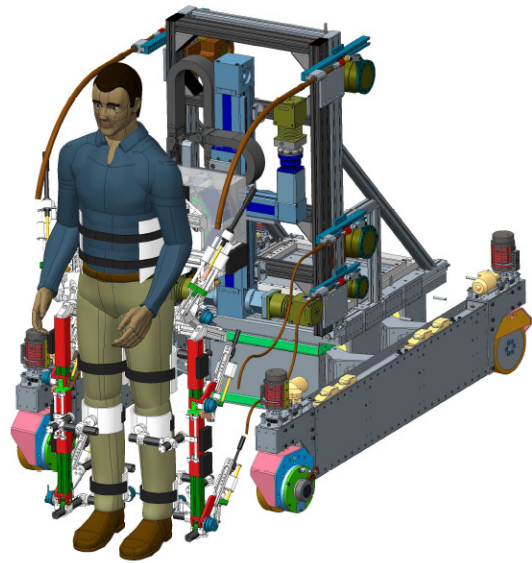

Figure 6. CAD of CORBYS rehabilitation platform.

weight transfer) and transversal (primarily associated with orientation of the body) planes. We also established that the range of movement in sagittal plane is considerably larger than in frontal or transversal planes but nonetheless combination of all movements is required for successful forward progression, weight transfer turning and balance. Inevitably the number of degrees of freedom of human lower extremities associated with human movement is considerably large. In rehabilitation exoskeletons the number of degrees of freedom directly defines the

Table 1.
Degrees of freedom as envisaged in mobile robotic gait rehabilitation system.

	Unit/Joint	Degree of freedom	Function in gait	Plane/axis of movement	Actuated/Passive	Remark
1	Mobile unit	Translation	Linear forward/backward		Actuated	
2			Linear medio/lateral	Transversal	Actuated	
3		Rotation	Turning	Transversal	Actuated	
4	Pelvis unit	Linear	Pelvis up/down movement	Z axis	Actuated	
5		Linear	Pelvis left/right movement	Y axis	Actuated	
6		Rotation	Pelvis rotation	Transversal	Passive	Spring preloaded
7		Rotation	Pelvis obliquity	Frontal	Passive	Spring preloaded
8	Hip joint	Rotation	Abduction/Adduction	Frontal	Passive	Spring preloaded
9		Rotation	Flexion/Extension	Sagittal	Actuated	
10		Rotation	External/Internal rotation	Transversal	Passive	
11	Knee joint	Rotation	Flexion/Extension	Sagittal	Actuated	
12	Ankle	Rotation	Dorsal/Plantar flexion	Sagittal	Actuated	
13		Rotation	Varus/Valgus	Frontal	Passive	Spring preloaded

likeliness of feasible movement to human natural movement. Ideally one would want the rehabilitation exoskeleton to cover all possible degrees of freedom that people utilize during walking. Only fully actuated rehabilitation exoskeleton would have the capacity to provide full support and corrective actions for complete human locomotion apparatus. This is technically not realistic. Depending on the application or types of target patient one must not only prioritize which degrees of freedom to include and which are less needed but also which should be actuated and which degrees of freedom are sufficient to be left passive. In recent years it has been shown that even relatively modest configuration can facilitate successful rehabilitation. Clinical evaluation of most famous representative of rehabilitation exoskeletons Lokomat, that integrates two actuated degrees of freedom per leg (hip and knee) and actuated vertical degree for pelvis movement, have demonstrated that such robot supported gait training improves gait function in a similar way as manually assisted gait training [3,5,6].

Therefore we suggest such design of mobile robotic gait rehabilitation system that aims at upgrading the existing state of the art by offering configuration that integrates thirteen degrees of freedom strategically selected to allow three dimensional gait training. Additionally we envisaged fully actuated support only in sagittal plane whereas providing only partial active support in frontal (actuated left-right pelvis movement) and transversal (actuated turning of mobile platform) planes. In general configuration complexity of rehabilitation exoskeleton is directly related to the patient capabilities. Namely in early phases of gait rehabilitation patient confronted with very weak neural motor control requires training of elementary gait mechanisms such as cyclical leg motion. In this case rather than leaving lower extremities unconstrained and managed by a weak neural control the patient may benefit more if certain degrees of freedom that are not directly associated with movements in sagittal plane were left confined or rigid. Eventually when gait function progressively improves rigid constraints begin to hinder rehabilitation progress as they prevent more challenging three dimensional training that involves weight transfer, turning and balancing. In this sense our conception of mobile robotic gait rehabilitation system aims at cognitively more fit subjects that have the capacity to deliver basic gait function but require further training to improve weight transfer, turning or balance.

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