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Redundant Kinematics and Workspace Centering Control of ASSISTON-GAIT Overground Gait and Balance Trainer

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***Abstract*— We present the redundant kinematics and workspace centering control of *AssistOn-Gait*, an overground gait and balance trainer designed to deliver pelvis-hip exercises to correct compensatory movements arising from abnormal gait patterns. *AssistOn-Gait* consists of an impedance controlled pelvis-hip exoskeleton module, supported by a motion controlled holonomic mobile platform. The exoskeleton module possesses 7 active degrees of freedom to independently control the rotation of the each hip in the sagittal plane along with the pelvic tilt, pelvic rotation and the horizontal, vertical and lateral displacements of the pelvis. The holonomic mobile base can track the movements of patients on flat surfaces, allowing patients to walk naturally, start/stop motion, vary their speed, sidestep to maintain balance and turn to change their walking direction. The kinematics of *AssistOn-Gait* is redundant, as the exoskeleton module spans all the degrees of freedom covered by the mobile platform. The device features dual layer actuation, since the exoskeleton module is designed for force control with good transparency, while the mobile base is designed for motion control to carry the weight of the patient and the exoskeleton. The kinematically redundant dual layer actuation enables the mobile base of the system to be controlled using workspace centering control strategy without the need for any additional sensors, since the patient movements are readily measured by the exoskeleton module. The workspace centering controller ensures that the workspace limits of the exoskeleton module are not reached, decoupling the dynamics of the mobile base from the exoskeleton dynamics. Consequently, *AssistOn-Gait* possesses virtually unlimited workspace, while featuring the same output impedance and force rendering performance as its exoskeleton module.**

I. INTRODUCTION

Walking constitutes a crucial part of patients' ability to perform daily activities and there exists a positive correlation between the ability to walk and the quality of life [1], [2]. Along these lines, gait rehabilitation is one of the most important neuro-rehabilitation therapies and there exists a continual search to establish more efficient techniques.

Natural walking necessitates a repetitious sequence of joint movements to be performed in coordination and harmony. Six determinants of gait pattern have been identified to lead to efficient locomotion, minimizing the displacements of the body center of gravity [3]. These determinants include *pelvic rotation* in the transverse plane, *pelvic tilt* in the coronal plane, the knee and hip flexion, the ankle plantar flexion, the foot and ankle rotations and the *pelvic displacements*. The irregularities in these determinants determine the difference between a natural or a pathological gait.

In this paper, we present the kinematically redundant design and the workspace centering control of *AssistOn-Gait*, an overground gait and balance trainer designed to deliver pelvis-hip exercises to correct compensatory movements arising from abnormal gait patterns. *AssistOn-Gait* consists of an impedance controlled pelvis-hip exoskeleton module that can assist pelvic movements of patients, attached to a motion controlled holonomic mobile platform that allows patients to walk naturally on flat surfaces, start/stop motion, vary their speed, sidestep to maintain balance and turn to change their walking direction.

II. RELATED WORK

Robots designed for gait rehabilitation can be loosely categorized into three groups: end-effector type, exoskeleton type with treadmill, and overground trainers with mobile bases. End-effector type robots connect to the patient from a single point (the foot) and movements/forces are applied to the patient only at this point. LokoHelp [4], Gait Trainer GT1 [5], HapticWalker [6] and MIT-Skywalker [7] are examples of end-effector type gait training devices. Since the movements of these robots do not correspond with human joints, joint specific therapies are not achievable with such devices, without using external restraints. Furthermore, these devices allow for compensatory movements of the patient, which may lead patients to adapt inefficient gait patterns.

Exoskeleton type robots are designed to correspond with human joints; therefore can successfully target joint specific therapies, by applying controlled torques to individual joints and measuring the movements of specific joints decoupled from the movements of other joints. Exoskeletons are commonly employed for body weight supported treadmill training (BWSTT). Many successful implementations of exoskeleton type lower limb rehabilitation robots have been developed in the literature, including Lokomat [8], LOPES [9] and ALEX [10]. These exoskeletons control the rotations of the hip and knee joints in the sagittal plane to mobilize the legs of the patient in a nominal gait pattern. However, these devices commonly restrict the natural movements of the pelvis, do not control the movements in the coronal plane. Furthermore, none of these devices assist the pelvic rotations and displacements that play a crucial role in the determination of the gait pattern. With a focus on the hip and knee rotations in the sagittal plane, these systems give minimal attention to balance and are ineffective against compensatory movements arising from abnormal gait patterns due to unnatural pelvic movements.

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Several exoskeletons can assist pelvis movements during treadmill training. Pelvic Assist Manipulator (PAM) utilizes six pneumatic cylinders to actuate 5 degrees of freedom (DoF) pelvic movements (pelvic tilt in the sagittal plane is kept passive) during BWSTT therapies [11]. Since the hip rotations are not a part of PAM, synchronizing the natural movement of the pelvis with the lower extremity movements is challenging and necessitates additional control effort [12]. Robotic Gait Rehabilitation (RGR) system [13] uses two single DoF linear actuators at both sides of the hip in order to partially assist pelvic movements. As this system only actuates movements in the vertical plane, the vertical pelvic displacement and pelvic tilt in the coronal plane can be supported actively, while other pelvic rotations and lateral pelvic displacement cannot be actively controlled.

Walking on the treadmill has been demonstrated to be significantly different from natural overground walking. Significant differences have been noted in cadence, stride length, stride angles, moments and power [14]. Analysis of pelvis kinematics during treadmill and overground walking has also revealed differences in pelvic rotation and obliquity [15].

Overground gait trainers possess mobile bases that follow/assist patients' walking movements on flat surfaces, allowing for gait practice under functional contexts and in combination with balance. These devices are advantageous, since the patients move under their own control, while experiencing all the sensory inputs associated with walking. Patients can start/stop motion, vary their walking speed as desired, sidestep to maintain balance and turn to change the walking direction. KineAssist [16], [17] and Walk Trainer [18], [19] are commercial examples of such overground gait trainers. Both devices consist of a mobile base connected to a pelvis orthosis and can provide partial body weight support. In particular, KineAssist is equipped with an admittance controlled Cobot base that compensates for the robot dynamics based on the forces measured at its custom designed torso-pelvis harness, which allows for passive movements of the pelvis. KineAssist complies with the natural user movements during walking but cannot assist pelvis/hip movements to help improve the quality of gait. Another overground trainer that relies on the interaction force measurements between the patient and the mobile base is proposed in [20], where unlike KineAssist, a holonomic mobile base is controlled according to these forces.

Walk Trainer features active pelvis and leg exoskeletons attached to a differential-drive mobile base [19]. Thanks to a parallel mechanism actuating all six DoF at the pelvis, the system has the ability to actively assist all the pelvic movements. Walk Trainer detects patient intentions regarding to walking speed and heading utilizing two potentiometers and can control its differential-drive mobile base to follow straight and curved paths.

NaTUre-gaits [21] is a similar device, consisting of pelvis and leg modules connected to a differential-drive mobile base. This system employs dual three DoF actuated Cartesian planar robots at each side of the hip to assist pelvic movements. These Cartesian planar robots are also used to measure local pelvic motions and these measurements are mapped to walking speed and heading angle to control the differential-drive mobile base of NaTUre-gaits to follow straight and curved paths.

Both WalkTrainer and NaTUre-gaits have relatively complex mechanical designs and possess passively non-backdriveable power transmission that necessitates the use of force sensors and active control algorithms to ensure synchronization between the mobile base, pelvis movements and leg rotations to achieve a natural gait for the patient. Furthermore, featuring differential drive mobile bases, both devices are non-holonomic and cannot allow for lateral movements, such as sidestepping.

In our previous work [22], we have presented an earlier version of ASSISTON-GAIT as a robot assisted overground gait rehabilitation device that consists of a pelvis-hip exoskeleton connected to a *series elastic* holonomic mobile base. The pelvis-hip exoskeleton module of the earlier version consists of two planar parallel mechanisms connected to patient with a custom harness to independently actuate 6 DoF of the pelvis-hip complex, while the mobile base relies on series-elastic actuation to compensate for the platform dynamics for transparency and for precise control of the assistance forces between the device and the patient. However, this earlier design possesses several performance bottlenecks that limit the usefulness of the device. Firstly, since the force control bandwidth of series elastic actuation is inherently limited (due to the use of a highly compliant force sensing element), the force rendering performance of the earlier design was also limited by this bandwidth for the DoF associated with the mobile base movements. Secondly, in the earlier design, the lateral pelvic displacement relied on the movements of the mobile base, which caused continual lateral movements of the base throughout the gait therapy.

In this paper, we propose design modifications and a control methodology to resolve both of these limitations. In particular, firstly, we add a redundant active DoF to the exoskeleton module to enable lateral pelvic displacements without the need for the movements of the mobile base. This addition ensures that *AssistOn-Gait* features dual layer (also called micro-macro) actuation [23], [24], since the exoskeleton module can now span all the DoF covered by its holonomic mobile platform. The redundancy is critical for the transparency of *AssistOn-Gait*, since this design decision makes sure that the reflected inertia of exoskeleton is independent of the inertia of the heavy mobile base that carries the weight of the patient and the exoskeleton [25]. Secondly, we implement a workspace centering motion controller [26]–[31] for the mobile platform based on pelvis poses measured by the exoskeleton module, such that the workspace limits of the exoskeleton module are not reached during overground training. This controller not only provides the device with a virtually unlimited workspace, but also decouples the dynamics of the mobile platform from the exoskeleton dynamics. Consequently, the force rendering performance and output impedance of *AssistOn-Gait* is dictated only by its exoskeleton module.

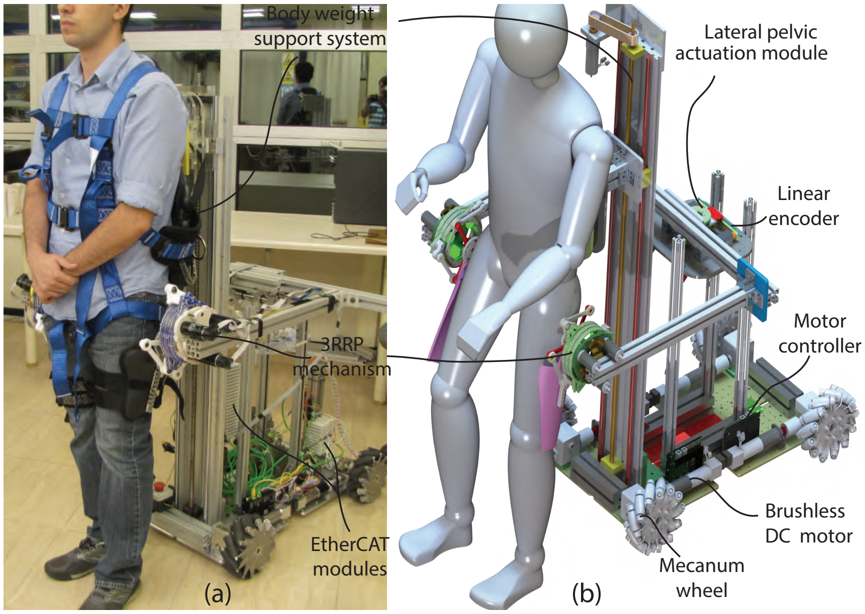

Fig. 1. (a) Prototype of *AssistOn-Gait* attached to a volunteer (b) Solid model of *AssistOn-Gait*

III. ASSISTON-GAIT

AssistOn-Gait provides patients with the ability to walk freely in all directions (forwards/backwards, turning, stepping sideways) while supporting their weight and actively controlling movements of their pelvis and hips. The holonomic mobile base follows the patient, carrying the weight of all the electrical and mechanical components. The hip-pelvis exoskeleton is capable of independently actuating 7 DoF of the hip-pelvis complex. Finally, the active Body Weight Support (BWS) module can provide dynamic compensation of the patient weight. Figure 1 presents an overview of *AssistOn-Gait* together with a prototype, while Figure 2 schematically depicts the kinematics of the device.

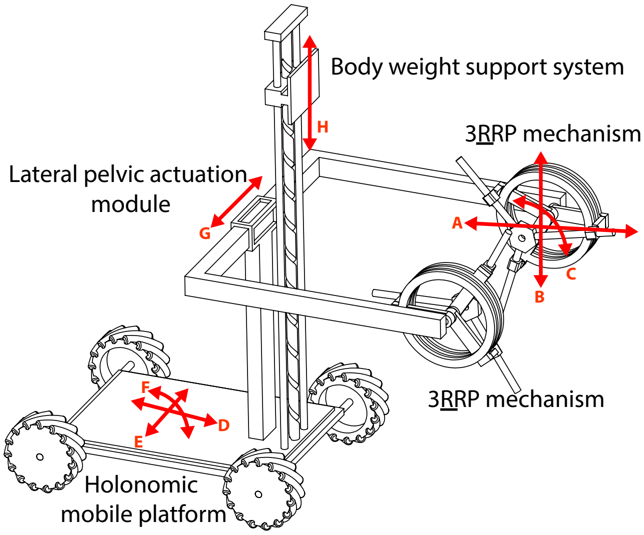

Fig. 2. Schematic detailing kinematics of *AssistOn-Gait*. For each 3RRP: A – forwards/backwards pelvic displacements and pelvic rotation in transverse plane, B – vertical pelvic displacement and pelvic tilt in coronal plane, C – rotations of the each hip in the sagittal plane; for the LPAM: G – lateral pelvic displacement; for the mobile base: D, E, F – holonomic movements in plane; for BWS: H – vertical motion.

A. Mobile Base

The mobile base consists of a platform with four Mecanum wheels independently driven by brushless DC motors. Each motor is controlled in hardware, by a controller capable of providing real time motion control at rates up to 10 kHz through an EtherCAT Master. The platform is designed with four independent wheel modules each consisting of a Mecanum wheel, DC motor, controller and gearbox. This modular design allows for varying the length and width of the mobile base according to task requirements. Overall, the holonomic mobile base is capable of accurate and fast movements along each direction with a motion control bandwidth of 6 Hz as characterized in [22]. The mobile base is not passively backdriveable in order to ensure patient safety by supporting the patient at all times and preventing falls.

B. Body Weight Support System

The active Body Weight Support System (BWSS) consists of a single DoF series-elastic actuator as presented in Figure 3. The series-elastic actuator of BWSS controls the vertical interaction force with the patient, compensating for the weight of the patient/device according to the rehabilitation task. The patient is connected to the BWSS by a harness equipped with a spinal back support. The harness features compliance for trunk rotations and lateral shift, but is rigid along the vertical direction to enable the series elastic element to detect upwards and downwards forces. The BWSS is not passively backdriveable to ensure patient safety by supporting the patient at all times.

C. Hip-Pelvis Exoskeleton

The exoskeleton module consists of dual 3RRP planar parallel mechanisms attached to a single DoF Lateral Pelvic Actuation Module (LPAM), as presented in Figure 1. In particular, the 3RRP mechanisms are attached to LPAM module at the both sides of the hip, while the LPAM module

TABLE I

HIP-PELVIS MOVEMENTS COVERED BY *AssistOn-Gait*

Degree of freedom	Active/passive	Delivered By	Device range of motion	Human range of motion
Vertical pelvic displacement	Active	Exo	± 100 mm	$3.7 \pm 0.8\%$ of leg length [32]
Lateral pelvic displacement	Active	Exo	± 50 mm	$\pm 40.8mm$ [33]
Forwards/backwards pelvic displacement	Active	Exo/mobile base	Unlimited	Unlimited
Pelvic tilt in coronal plane	Active	Exo	$\pm 12^\circ$	$9.4^\circ \pm 3.5^\circ$ [32]
Pelvic rotation in transverse plane	Active	Exo	$\pm 10^\circ$	$\pm 6^\circ$ [34]
Hip flexion/extension	Active	Exo	$30^\circ/30^\circ$	$30^\circ/10^\circ$ [35]
Side stepping	Active	Exo/mobile base	Unlimited	Unlimited
Turning	Active	Exo/mobile base	Unlimited	Unlimited

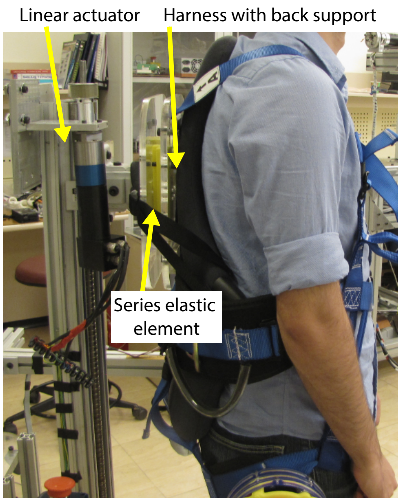

Fig. 3. Active body weight support system connected to a volunteer

is attached to the mobile base. The exoskeleton module of *AssistOn-Gait* possesses 7 DoF to actively control the rotations of the both hips in the sagittal plane, pelvic tilt in the coronal plane, pelvic rotation in the transverse plane, as well as forward/backward, vertical and lateral displacements of the pelvis as depicted in Figure 2. All these DoF can be controlled independently or in a coordinated manner. LPAM allows for the full range of lateral pelvic displacement, while the dual 3$\underline{R}$RP mechanisms can cover the whole range of pelvic rotations and pelvic tilt that take place during natural walking. Thanks to its underlying kinematics, the pelvis-hip exoskeleton can mimic natural gait patterns and assist all of the crucial pelvic movements required for achieving proper gait during overground walking.

In this paper, the measurement of pelvis movements during walking is required to implement the workspace centering controller of the mobile base. Our current implementation of the hip-pelvis exoskeleton is based on passively backdriveable LPAM and 3$\underline{R}$RP mechanisms, which rely on direct drive actuation with capstan transmission; hence, these measurements can be performed without actuating/controlling the exoskeleton module. However, passive backdriveability is not crucial for workspace centering controller, since admittance control or closed loop impedance control can be used to render the system actively backdriveable to allow for these measurements.

Note that the exoskeleton module can span all the DoF covered by the holonomic mobile platform and possesses enough workspace for a full stride. Hence, together with the BWSS, this module can also be employed to assist pelvis movements during treadmill training.

D. Kinematic Redundancy and Dynamic Decoupling

When the exoskeleton module is attached to the mobile base, the overall system possesses 3 redundant active DoF, as listed in Table I. In particular, the exoskeleton module already covers all the of motions of the holonomic mobile platform, resulting in the redundancy. This redundancy is a design choice and is critical for ensuring transparent force control of the device. Thanks to this kinematic redundancy, the overall system can be decomposed into two subsystems, referred to as micro and macro structures. The micro structure is defined as the smallest distal set of DoF that can completely span the operational space, while the macro structure connects the micro structure to the ground. For *AssistOn-Gait*, the exoskeleton serves as the micro structure and the mobile base constitutes the macro one. Since, the reflected inertia of a kinematically redundant robot is upper bounded by the inertial properties of the micro structure [25], *AssistOn-Gait* inherits the inertial properties of its exoskeleton module and is independent of the inertia of the mobile base. Given the high inertia of the mobile base, this inertial decoupling is crucial for archiving good force control performance within a large force control bandwidth.

Furthermore, it has been shown that if the friction/damping forces between the mobile base and the exoskeleton can be kept low, then the dynamics of the exoskeleton can be completely decoupled from the dynamics of the mobile base, as long as the workspace limits are not reached [26], [30]. The friction/damping forces can be kept low by active compensation of exoskeleton dynamics under closed loop force/impedance control architectures or through mechanical design, by minimizing frictional losses at the power transmission elements. In our current implementation, the actuation of the hip-pelvis exoskeleton is based on direct drive actuation with capstan transmission and the overall system features low friction forces resulting in a excellent passively backdriveability [36].

IV. WORKSPACE CENTERING CONTROL

In many situations, it is desirable to increase the workspace of an existing device to achieve better and more realistic interaction. Interactions of this type have been introduced in [23] and further explored in [24], where a high performance (micro) robot has been mounted on a larger (macro) robot in order obtain enhanced functionality. This concept has also been applied to haptic interaction [26]–[31], [37]–[39] to enhance the workspace of small haptic devices. Furthermore, transparency of high fidelity force-feedback devices attached to mobile bases has been investigated in [26],

[30]. It has been shown that the force rendering capabilities of the overall device is equivalent to that of the high fidelity force-feedback device, if the mobile base can keep the user always within the workspace limits of the force-feedback device and the friction/damping losses between the mobile base and the force-feedback device can be kept low. It has also been discussed that the best performance from the coupled system can be achieved when the high performance (micro) robot is kept close to its ideal operating point through fast enough movements of the macro structure.

AssistOn-Gait possesses micro-macro dual layer actuation, where an exoskeleton with high force/impedance control performance is mounted on a mobile platform in order obtain enhanced functionality. Figure 4 presents the normalized manipulability contours of the 3$\underline{R}$RP mechanism of the exoskeleton module over its workspace. It can be observed from this figure that the highest manipulability is achieved when the end-effector of the mechanism is at the center of its workspace and manipulability decreases towards the boundaries of the workspace.

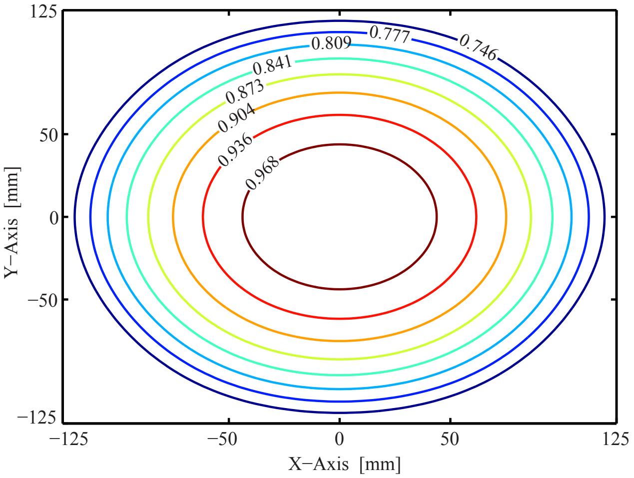

Fig. 4. Manipulability of the 3$\underline{R}$RP mechanism of the exoskeleton module

We implement a workspace centering motion controller [26]–[31] for the mobile platform based on pelvis poses measured by the exoskeleton module, such that the workspace limits of the exoskeleton module are not reached during gait training. This controller not only provides the system with a virtually unlimited workspace, but having 6 Hz motion control bandwidth, this controller is fast enough to decouple the dynamics of the mobile platform from the exoskeleton dynamics during rehabilitation therapies. Consequently, since the exoskeleton is highly passively backdriveable and its workspace limits are not reached during gait and/or balance therapies, the force rendering performance and output impedance of *AssistOn-Gait* is dictated only by the design of its exoskeleton module.

The exoskeleton module can span all the DoF covered by the holonomic mobile platform and possesses enough workspace for at least one full stride. The goal of the mobile platform is to carry the weight of the patient and device with minimal intervention. Furthermore, the less the mobile base moves, the more acceptable it is for use in social environments. Along these lines, virtual fixtures based on nominal gait thresholds are to implemented for the workspace centering control of *AssistOn-Gait.* These fixtures are defined with respect to the mobile platform. The controller is implemented such that the mobile platform does not move unless the patient pose comes in contact with the fixtures. If the patient violates these virtual fixture constraint, the penetration distance and direction are calculated, and the motion of the mobile base is controlled to eliminate this violation.

Unlike in the mobile haptic interface applications, the mobile platform does not move for every pose change of the patient. In particular, the thresholds are selected such that during straight walking, the mobile base does not have any lateral or rotational movements, since repetitive motions of the pelvis along these DoF can be safely kept within the workspace of the exoskeleton module. However, the thresholds are exceed if the patient decides to turn or side-step and the mobile base moves accordingly to comply with these movements.

The workspace centering controller of *AssistOn-Gait* operates based on measurements provided by the exoskeleton module. Note that, only the relative measurements between the mobile base and the exoskeleton module are required for the implementation of this controller. During walking, the pelvis-hip complex has complex translational and rotational movements; however, the vertical projection of these motions on the floor is of interest for the control of the mobile base. In particular, relevant movements are caused by the rotation of the pelvis in the transverse plane, flexion/extension of the hips in the sagittal plane, forwards/backwards pelvic displacement along the direction of walking and lateral pelvic displacement during walking or side stepping. Thanks to the encoders installed on the LPAM and 3$\underline{R}$RP mechanisms of the exoskeleton module, the relative configuration of left and right hip joints, as well as the lateral position of the pelvis can be calculated in real-time. These measurements are used for the workspace centering control, as shown in Figure 5. In the figure, the direction of forward walking is denoted by the x-axis, the direction of sidestepping is denoted by the y-axis and the axis of rotation for turning is given by the z-axis.

The 3$\underline{R}$RP mechanisms and LPAM have corresponding physical workspace limits and to achieve the desired level of performance, it is imperative that the controller can keep the patient within these limits, by moving the mobile base accordingly. For this purpose, along the x axis, the estimations x_r and x_l are available, which represent the coordinates of the right and left hip joints, respectively. Along the y axis, LPAM directly measures the lateral displacement of the pelvic joint. Based on these measurements, the relative displacement x_p of the patient along the x axis and the heading angle θ_p of the patient with the x-axis can be calculated using x_r and x_l, while the relative y_p displacement of the patient along the y axis corresponds to the LPAM measurement.

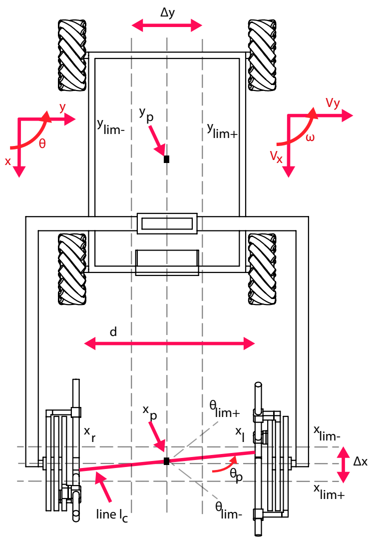

Fig. 5. Determination of patient pose through positions measured by the exoskeleton module

V. EXPERIMENTAL VERIFICATION

For the experimental verification, a healthy volunteer (28 years old male) was connected to *AssistOn-Gait* and asked to walk naturally along a predefined path, while avoiding obstacles as depicted in Figure 6. The participants signed a consent form approved by the IRB of Sabanci University. During the experiment physical obstacles were used, even though *AssistOn-Gait* can also generate virtual fixtures as demonstrated in [22]. The volunteer was asked to start walking forwards, then stop, sidestep to avoid the obstacle and then turn along a defined path. The workspace centering controller were active during the trials. The goal of the workspace centering controller is to ensuring that the displacements/angles of the pelvis-hip complex remain within pre-defined limits of the exoskeleton workspace. Several tests were carried out and representative trajectories corresponding to each phase of the task are presented in Figure 7.

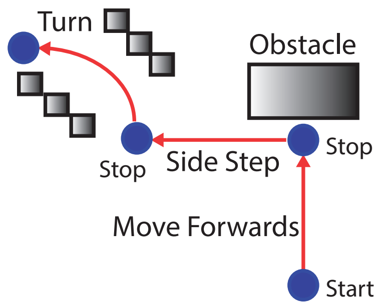

Fig. 6. Experiment protocol

In Figure 7, the first row depicts left hip displacement trajectories during forward walking with the virtual fixtures set at ±10 mm, the second row presents lateral displacement trajectories of the volunteer during side stepping with the virtual fixtures set at ±35 mm and the third row plots the pelvic rotation angle trajectories during turning with the virtual fixtures set to 8°. Success of the experiment is evaluated by studying two factors: the exoskeleton must not reach the limit of its physical workspace and the mobile base should properly follow the volunteer without leading or lagging his motion.

It can be observed from the Figure 7 that the volunteer can move (forwards, sideways) and turn freely within the virtual fixtures without invoking any mobile base movements. Furthermore, it can be observed that the virtual fixtures are not violated (all movements stay within the predetermined regions), indicating that the mobile base can compensate human motions in a timely manner to ensure the desired level of performance, satisfying the requirements of workspace centering motion control.

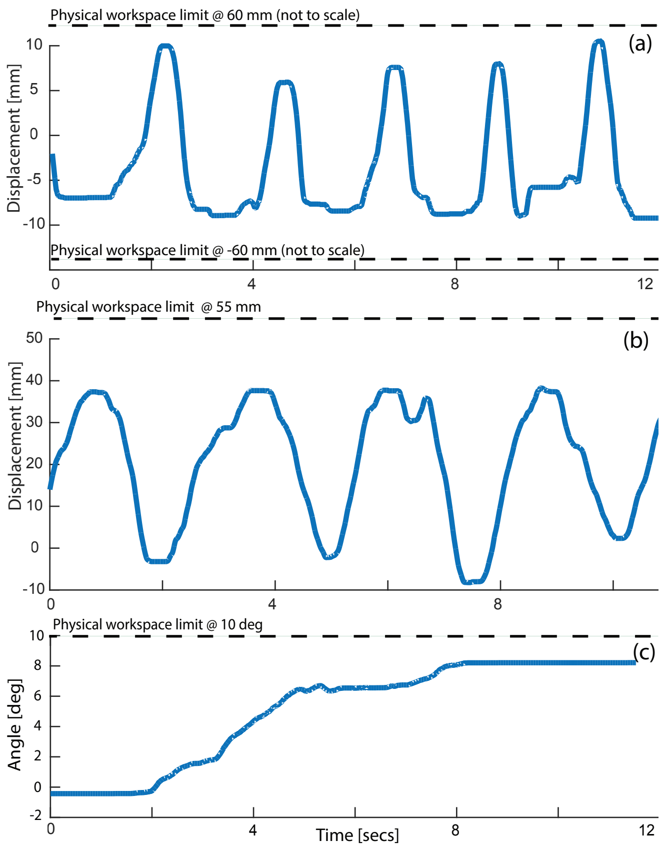

Fig. 7. Experiment results: (a) Left hip displacement trajectories during forward walking with virtual fixtures set at ±10 mm, (b) Lateral human displacement trajectories during side stepping with virtual fixtures set at ±35 mm and (c) Pelvic rotation angle trajectories during turning with a virtual fixture set at 8°.

VI. CONCLUSIONS AND FUTURE WORK

We have presented the redundant kinematics and workspace centering control of *AssistOn-Gait*, together with their experimental verification. We have argued that the kinematic redundancy between the mobile base and the exoskeleton module is crucial to ensure best possible force rendering performance and capitalized on this redundant kinematics to control the movements of the mobile base through position measurements of the exoskeleton module. The proposed workspace centering controller is implemented with mobile base that is fast enough to ensure that the workspace limits of the exoskeleton module are not reached, resulting in an unlimited overground training workspace for *AssistOn-Gait*. Furthermore, coupled to the passively backdriveable exoskeleton module, the workspace centering controller serves a crucial role by dynamically decoupling the mobile base and the exoskeleton module.

Future works include utilizing the redundant vertical DoF of the exoskeleton module to improve performance of the BWSS and conducting case studies with stroke patients.

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