Original Article

Institution of MECHANICAL ENGINEERS

Journal of ENGINEERING IN MEDICINE

Proc IMechE Part H:
J Engineering in Medicine
2018, Vol. 232(6) 619–627

DOI: 10.1177/0954411918776682
journals.sagepub.com/home/pih
SAGE

Influence of the amount of body weight support on lower limb joints' kinematics during treadmill walking at different gait speeds: Reference data on healthy adults to define trajectories for robot assistance

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Abstract

Several robotic devices have been developed for the rehabilitation of treadmill walking in patients with movement disorders due to injuries or diseases of the central nervous system. These robots induce coordinated multi-joint movements aimed at reproducing the physiological walking or stepping patterns. Control strategies developed for robotic locomotor training need a set of predefined lower limb joint angular trajectories as reference input for the control algorithm. Such trajectories are typically taken from normative database of overground unassisted walking. However, it has been demonstrated that gait speed and the amount of body weight support significantly influence joint trajectories during walking. Moreover, both the speed and the level of body weight support must be individually adjusted according to the rehabilitation phase and the residual locomotor abilities of the patient. In this work, 10 healthy participants (age range: 23–48 years) were asked to walk in movement analysis laboratory on a treadmill at five different speeds and four different levels of body weight support; besides, a trial with full body weight support, that is, with the subject suspended on air, was performed at two different cadences. The results confirm that lower limb kinematics during walking is affected by gait speed and by the amount of body weight support, and that on-air stepping is radically different from treadmill walking. Importantly, the results provide normative data in a numerical form to be used as reference trajectories for controlling robot-assisted body weight support walking training. An electronic addendum is provided to easily access to such reference data for different combinations of gait speeds and body weight support levels.

Keywords

Body weight support, treadmill training, robot assisted-gait rehabilitation, on-air stepping, gait kinematics

Date received: 5 January 2018; accepted: 23 April 2018

Introduction

There is increasing interest in using robotics associated with body weight support treadmill training (BWSTT) to assist locomotor training following damages to the central nervous system such as stroke, traumatic brain injuries, and spinal cord injuries.[1,2]

During BWSTT, patients are trained to produce rhythmic gait cycles on a treadmill with a body weight support (BWS) system attached through a harness. The neurorehabilitation principle behind BWSTT is to allow for repeated, intensive task-oriented exercises which stimulate motor (re)learning of the participant,[2] prevent stiffening of joint tissues, reduce spasticity, and provide somatosensory stimulation which helps inducing brain plasticity.[3]

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To perform such exercises in the early stages after injury, when the possibility to obtain the above therapeutic effects is maximized, BWS is needed, to face against muscular weakness and reduced balance. The amount of weight support is then reduced as muscular strength and motor control improve.

During BWSTT, therapists have to manually move the patients' paretic legs continuously, to produce repetitive gait cycles and to make the automation of this training process possible.

This is a tiring task for therapists, which limits the duration of the training session; moreover, the quality of leg trajectory and the stride-to-stride repeatability are not easily controlled and are therapist-dependent.[4]

The use of robots may provide a solution to these problems. The general idea is to exploit specific properties of robotic devices: to interact physically with the patient's limbs in order to induce coordinated multijoint movements within a complex motor task like walking, stepping, and ascending/descending stairs. In this perspective, several robotic devices have been developed based on two different design approaches: exoskeleton (e.g. the Lokomat, Hocoma AG, Switzerland) or endpoint (e.g. the GaitTrainer, Reha-Stim, Germany or G-EO system, Reha Technology AG, Switzerland).

In post-stroke patients, the effectiveness of robotic locomotor training on the walking capability improvement has been deeply investigated. Although some studies found no significant differences in primary outcomes when conventional (therapist-assisted) and robotic locomotor training are compared,[5,6] most of the clinical trials indicated that robotic training alone or the combination of robotic and conventional training is superior to conventional therapy alone in terms of gait function recovery.[4,7–13]

The effect of combined robotic locomotor training and cognitive protocols has been studied in neurological patients. Sacco et al.[14] developed a robotic and cognitive gait rehabilitation (RCGR) protocol, using an active exoskeleton (Pneumatic Interactive Gait Rehabilitation Orthosis, PIGRO).[15] The strength of this protocol lies in the integrated use of both sensorimotor and cognitive stimulations. The proprioceptive and kinesthetic activation induced by the passive leg movements provides constant afferent input to the motor control centers, facilitating central pattern generators and enhancing motor drive; also, such proprioceptive sensations are essential for the parallel cognitive training. On the other hand, the mental imagery employed during the robotic-assisted motion focuses the patient's conscious attention on the ongoing steps. Preliminary results in healthy participants showed that the RCGR protocol modifies sensorimotor activation of the brain, leading to greater activation of the premotor and supplementary motor areas, the primary motor and somatosensory areas of the dominant hemisphere, as well as an increasing functional connectivity within the motor network.[16,17] The efficacy of such training has been proved on patients with chronic traumatic brain injury and major gait impairments.[14] Besides improvements on physiatric functional scales and daily living activities, patients showed post-training greater activation in the sensorimotor and supplementary motor cortices, as well as enhanced functional connectivity within the motor network.

There are several strategies to control robots for gait rehabilitation, however, they can essentially be divided into two main categories:[4] trajectory tracking (TT) and assist-as-needed (AAN) control. In TT control, also known as position control, the robot moves patients' lower limbs along certain predefined paths similar to what therapists perform during manual treadmill training. This is performed at feet level for endpoint robots and at each joint level for exoskeleton robots, where hip, knee, and ankle joints are guided individually. In TT control strategy, the patient is guided through the imposed trajectories, regardless of his active participation in the task. Conversely, in AAN control strategy, the robotic devices only supply as much effort as a patient needs to accomplish the locomotor task. This means that the controlled variables are the torques (or forces) produced by the robot on the subject, rather than the trajectory of the joints (or end effector): as long as the patient moves along a desired trajectory (or within a given boundary around a trajectory), the robot should not intervene, while when the subject deviates from the desired trajectory, the robot should create a correcting torque/force.[1] AAN control is obtained with a variety of different implementations, which include impedance control,[18] patient-cooperative path control,[19] and trajectory adaptation control.[20]

Anyway, despite their different approaches, almost all control strategies developed for robotic locomotor training need a set of predefined trajectories as reference input for the control algorithm. The reference trajectories are usually derived from healthy subjects walking unsupported: either from specific experiments[19] or, more frequently, from the literature.[21] In the case of hemiparetic subjects, reference trajectories can be recorded in real time from the unaffected limb.[22,23]

On the other hand, it is known that lower limb kinematics during walking is affected by the gait speed[24] and by the amount of body weight support,[25] although the effects of these factors have been not wholly addressed so far and no comprehensive reference database is still available. Indeed, these aspects are not taken into proper consideration and commercial devices for robotic BWSTT use standard gait analysis data as reference trajectories.

Based on the above, the goals of this work were twofold: (1) to jointly and extensively analyze the changes induced in the kinematics of lower limb by different amounts of BWS at different gait speeds during the treadmill walking of healthy subjects and (2) to provide such normative data in numerical form to be used as reference trajectories for controlling robot-assisted BWSTT.

Methods

Subjects

Ten male healthy volunteers (age range = 23–48 years, mean age = 27.9 years, standard deviation (SD) = 7.3

years) took part in the experiment. Exclusion criteria were gait impairment, history of neurological or developmental illness, mental disorders, drug or alcohol abuse, current use of medications known to alter neurological activity, stature over 185 cm, and weight over 85 kg. The limitations of subjects' height and weight were determined, respectively, by the dimensions and counterweights of the BWS system used in this study (see below).

All participants gave written consent to participate in the study, which was approved by the local Ethical Committee. Demographic and anthropometric information about our study-specific sample is provided in Table 1.

Experimental protocol

Subjects were asked to walk on a treadmill (Carnielli, model CTP801, electrical engine peak power: 2570 W, speed range: 0.8–20 km/h, speed step: 0.2 km/h) in four different conditions of BWS: no support (0%), 20%, 40%, and 60% BWS. In addition, a trial with full BWS (100%), that is, with the subject suspended on air, was performed. This particular condition was analyzed because it might be useful, as proposed in Sacco et al.,[14] for robotic-assisted locomotor rehabilitation of severely affected patients who are unable, in the first sessions, to walk over a treadmill with partial BWS. In this latter trial the subject was asked to move his legs on air, mimicking the walking pattern and trying to move all joints in a continuous, alternate, and smooth way. Since during on-air trial the subject was not touching the treadmill with his feet, to control stepping cadence, a metronome was used and the subject was asked to follow it, each ticking being the pace for a step.

The BWS system was a custom-made device (see Figure 1(a)) consisting of an aluminum frame which sustained a body harness, through two ropes fixed at shoulder level, two pulleys and, on the other end of each of the ropes, a set of selectable counterweights. The treadmill was inserted into the frame of the BWS system.

Each of the four different BWS conditions was repeated for five different treadmill speeds, set, respectively, at 0.2, 0.4, 0.6, 0.8, and 1 body height/s (BH/s) and named, respectively, XS, S, M, L, and XL. The treadmill speeds were set at given percentages of BH to allow direct comparison among subjects with different heights. The "on-air stepping" trials were performed only at two gait cadences, corresponding to those registered in ad hoc trials at 90% BWS with a treadmill speed of, respectively, 0.2 and 0.4 BH/s.

For each condition, the subject was allowed to become familiarized with the specific gait speed and weight unloading level, then we registered kinematics for about 30 consecutive steps (15 right and 15 left steps). To minimize the possible effects of any transient phenomena, only the 20 central steps were then considered for the subsequent analysis.

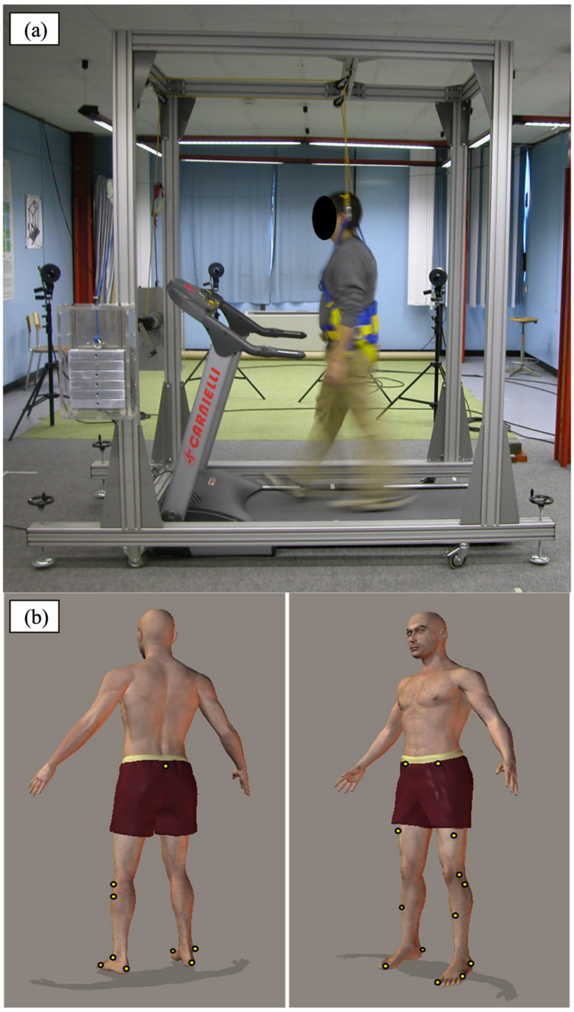

Figure 1. (a) Picture of the body weight support system and the treadmill used in this study. Three TV cameras of the motion analysis system are visible in the picture. (b) Marker positioning according to LAMB protocol (pelvis + lower limb component).[26]

Table 1. Demographic and anthropometric characteristics of the subjects included in the study.

Subject ID	Age (years)	Body height (cm)	Body weight (kg)
S1	27	175	72
S2	26	177	74
S3	26	182	75
S4	24	171	66
S5	25	180	75
S6	23	174	65
S7	25	180	70
S8	30	184	80
S9	48	175	72
S10	25	175	80

Motion analysis technique

A 9-camera optoelectronic motion capture system (SMART, BTS, Milano, Italy) was used to detect the three-dimensional (3D) trajectories of 10-mm diameter spherical retroreflective markers (sampling rate 200 Hz, accuracy below 0.3 mm) attached onto specific anatomical landmarks and moving inside the calibrated volume of 1.9 × 2.1 × 1.5 m (L × H × W).

The adopted set of passive markers complied with the LAMB protocol.[24,26] It required the positioning of 19 markers on specific anatomical landmarks (Figure 1(b)) and allowed for a full 3D description of joints' kinematics bilaterally.

Data elaboration and analysis

In this study, among the variables available from the LAMB protocol, the lower limb sagittal joint angles (hip, knee, and ankle) and the pelvis orientation angles (pelvis tilt, obliquity and rotation) have been considered, since they include the kinematic variables controlled by actually available robotic BWSTT systems.[15,19–21] Even considering powered exoskeletons to assist overground walking, a recent comprehensive review by Yan et al.[27] concluded that most of these systems aim to provide active assistance at lower limb joints in the sagittal plane only. The significant events of the gait cycle, that is, the foot strike and foot off, were identified by looking for the most anterior (foot strike) and the most posterior (foot off) position of a foot marker.

For each subject, for each trial, all the considered variables were stratified, after being time-normalized cycle-by-cycle, and then the median profile extracted as the representative one. The choice of the median operator, preferred to the mean operator, aims at reducing the effect of abnormal gait cycles, possibly occurring during such a peculiar experiment.

To summarize, a total of 440 kinematic trajectories were captured and considered in this study: (4 (BWS conditions) × 5 (gait speeds) × 10 (subjects) × 2 (sides)) + (1 (100% BWS) × 2 (speeds) × 10 (subjects) × 2 (sides)).

A statistical analysis on the main parameters extracted from kinematic trajectories (ROM, timing of maxima and minima) was performed with Statistica (Statsoft Inc., USA) to test for the significant effects of speed and side (repeated measures analysis of variance (ANOVA) 5 × 2) and BWS and side (repeated measures ANOVA 4 × 2) for treadmill trials. Moreover, paired t-tests were performed to check for significant differences between on-air stepping (100% BWS) and treadmill walking at different BWS, for the trials at S and XS speed.

Since no parameter showed a significant effect of side, the two sides were then pooled together.

The final reference profiles, for each considered variable, was thus obtained, for each speed and for each level of weight support, by averaging the individual profiles of 20 lower limbs (10 right and 10 left limbs).

Results

Figure 2 reports the values of gait cadence for each BWS condition and gait velocities. It appears that, as expected, a reduction in gait speed was associated with a reduction in gait cadence ($p < 0.05$ for ANOVA and all post hoc Bonferroni-corrected comparisons). Conversely, the amount of BWS showed no significant influence on gait cadence, except for full body support, where cadence was however externally determined with a metronome.

The trajectories of sagittal joint angle (hip, knee, and ankle) and pelvis orientation angle (tilt, obliquity, and rotation) in the five different BWS conditions (0%, 20%, 40%, 60%, and 100% BWS) and at the five different gait velocities are reported in an electronic addendum as numerical values (see supplementary material): (a) for each subject and both sides and (b) averaged among all subjects and sides, as reference profiles.

To facilitate the analysis of such a large amount of data, in the next figures we report the time course, averaged among all subjects, of angular displacements of pelvis and lower limb joints in two specific conditions: in Figure 3 the influence of different gait speeds is shown for a 60% BWS (an intermediate level between no BWS and full BWS); conversely, in Figure 4 the effect of different amounts of BWS is shown for a gait speed of 0.4 BH/s, a quite low velocity, typical for robotic BWSTT. To allow for a complete analysis of all the considered conditions, in Figure 5 we report the value of specific curve parameters throughout all conditions, averaged among all subjects. In particular, the ROM of pelvis movements are reported in Figure 5(a)–(c), the ROM of joint angles are reported in Figure 5(d)–(f), and the values of specific time events are shown in the bottom graphs of Figure 5. Specifically, they are the timing of maximal hip extension (Figure 5(g)), the timing of knee maximal flexion during swing (Figure 5(h)), and the timing of maximal ankle plantar-flexion (Figure 5(i)), indicative of end of push-off phase.

A main effect of gait speed was found for all ROMs and timing parameters (ANOVA, $p < 0.05$). A main effect of BWS was found for hip and knee ROM, and for the timing parameters of joint kinematics (ANOVA, $p < 0.05$). The condition of full BWS showed significant differences compared to all other partial BWS conditions, at matched speeds, for all joints' ROM (except for ankle ROM at XS speed) and timing parameters (paired t-tests, $p < 0.05$).

Discussion

In this article we systematically analyzed the effects of different BWS levels, at various gait speeds, on lower limb kinematics during treadmill training, with the aim

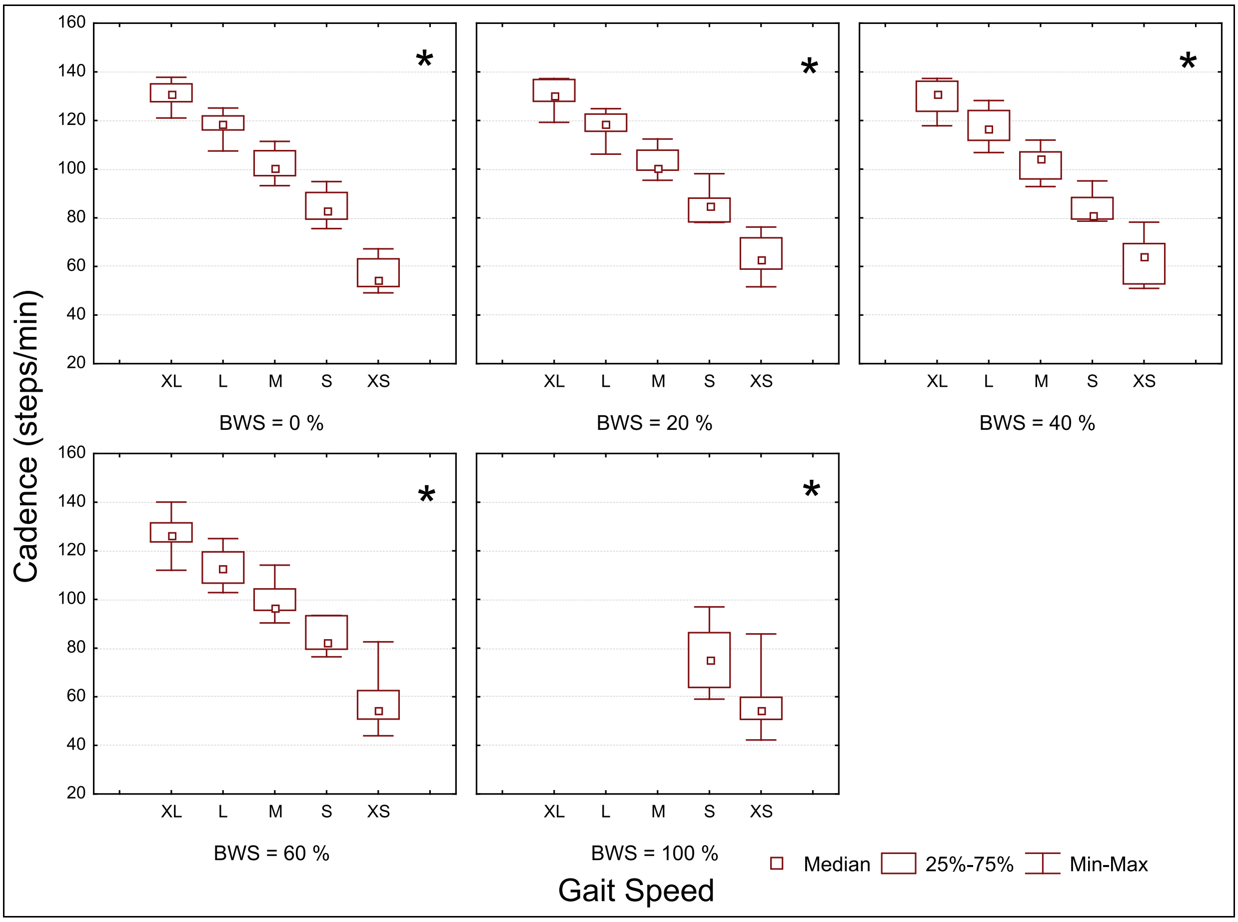

Figure 2. Gait cadence at different levels of BWS and gait speeds.
*$p < 0.05$ (for ANOVA and all Bonferroni-corrected post hoc comparisons).

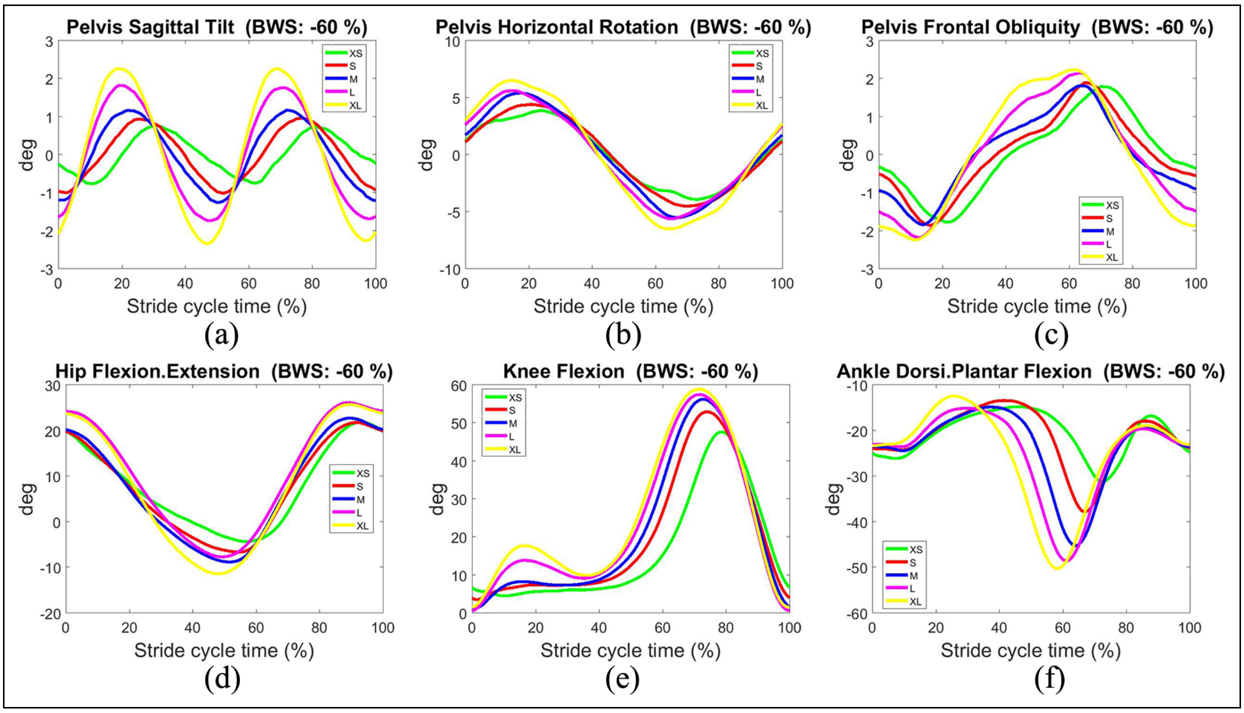

Figure 3. Effects of gait velocity (color code) on the temporal profiles of pelvis (tilt (a), rotation (b), obliquity (c)) and lower limb joints (hip (d), knee (e), ankle (f)) angular displacements. Support was set at 60% BW. Profiles are averaged among all subjects. Gait velocity code: XS = 0.2 BH/s, S = 0.4 BH/s, M = 0.6 BH/s, L = 0.8 BH/s, XL = 1 BH/s.

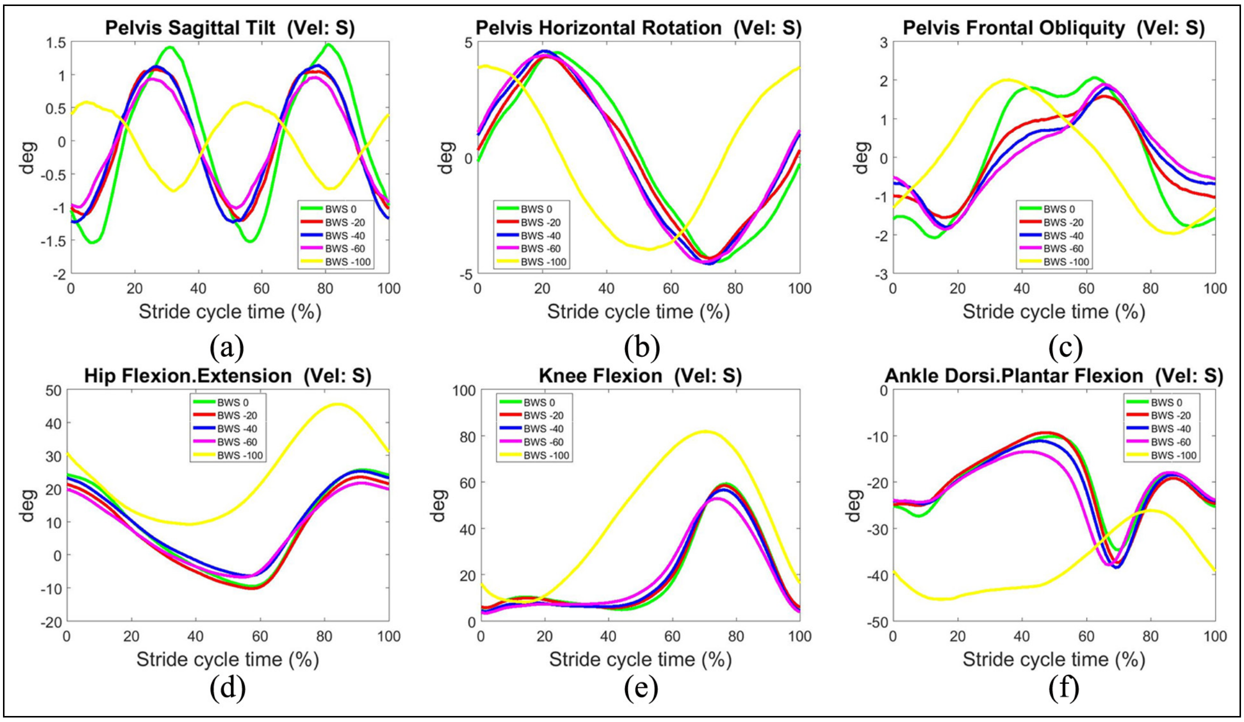

Figure 4. Effects of BWS level (color code) on the temporal profiles of pelvis (tilt (a), rotation (b), obliquity (c)) and lower limb joints (hip (d), knee (e), ankle (f)) angular displacements at S gait velocity (0.4 BH/s). Profiles are averaged among all subjects.

to provide reference trajectories for controlling robot-assisted BWS treadmill training.

In accordance with previous studies performed overground[24] and on treadmill,[28] we found that the slower the speed, the smaller is the ROM of the pelvis and of all lower limb joints. Moreover, with slower speed, we found an increasing delay in the timing of the peaks within the gait cycle for all joints and the pelvis (Figures 3 and 5). It is interesting to note that at the knee joint, in addition to the peak of flexion during swing, also the first peak of flexion at the beginning of stance phase decreases for slower speeds, even disappearing for gait speeds slower than 0.6 BH/s (M speed in Figure 3(e)). At the ankle joint, there is a strong reduction of plantarflexion peak for decreasing speeds (Figure 3(f)).

Concerning the effect of different levels of BWS, Figures 4 and 5 show that increasing BWS does not affect significantly pelvis kinematics and ROM, while it slightly reduces hip and knee ROM, and anticipates the peaks of movement in the gait cycle at all joints.

Van Hedel et al. suggested that BWSTT should be performed at a minimal walking speed of 2.5 km/h and a BWS of less than 50%, since over these values the walking pattern is highly altered with respect to normal.[28] However, this might be too intensive for some patients and, in such cases, reference trajectories from healthy subjects walking in similar altered conditions should be used to control robot, in place of unsupported normal walking trajectories typically used by commercial devices. As a matter of fact, these reference data at low gait speeds and high BWS were not available numerically so far, therefore, the data reported in attachment to this article are an important contribution in the field and represent the main originality of this study.

As expected, the condition of full BWS showed very different kinematic patterns both at the pelvis and at all lower limb joints and deserves a separate discussion. In this condition the subject is stepping on air, therefore, his feet are not guided, during the stance phase, by the treadmill backward movement. As a consequence, the ankle joint heavily changes his classical double dorsiflexion pattern, showing a general offset toward a more plantarflexed posture and only one dorsiflexion movement of reduced amplitude, during the forward oscillating phase. Conversely, the hip and knee joints increase their ROM, mainly because of an increased peak of flexion during the swing phase, likely to compensate for the reduced clearance of the foot. Also, the pelvis shows a significant change of kinematic pattern in all anatomical planes, particularly in terms of temporal phase, which is even opposite with respect to overground pattern as regards tilting movement in the sagittal plane (Figure 4(a)).

Our results of very different kinematic patterns between overground walking and full BWS walking are in accordance with previous studies of human locomotion in a wide range of walking speeds and gravitational loads, including on-air stepping.[29,30] These studies demonstrated a remarkable constancy of the velocity–curvature relationship across different

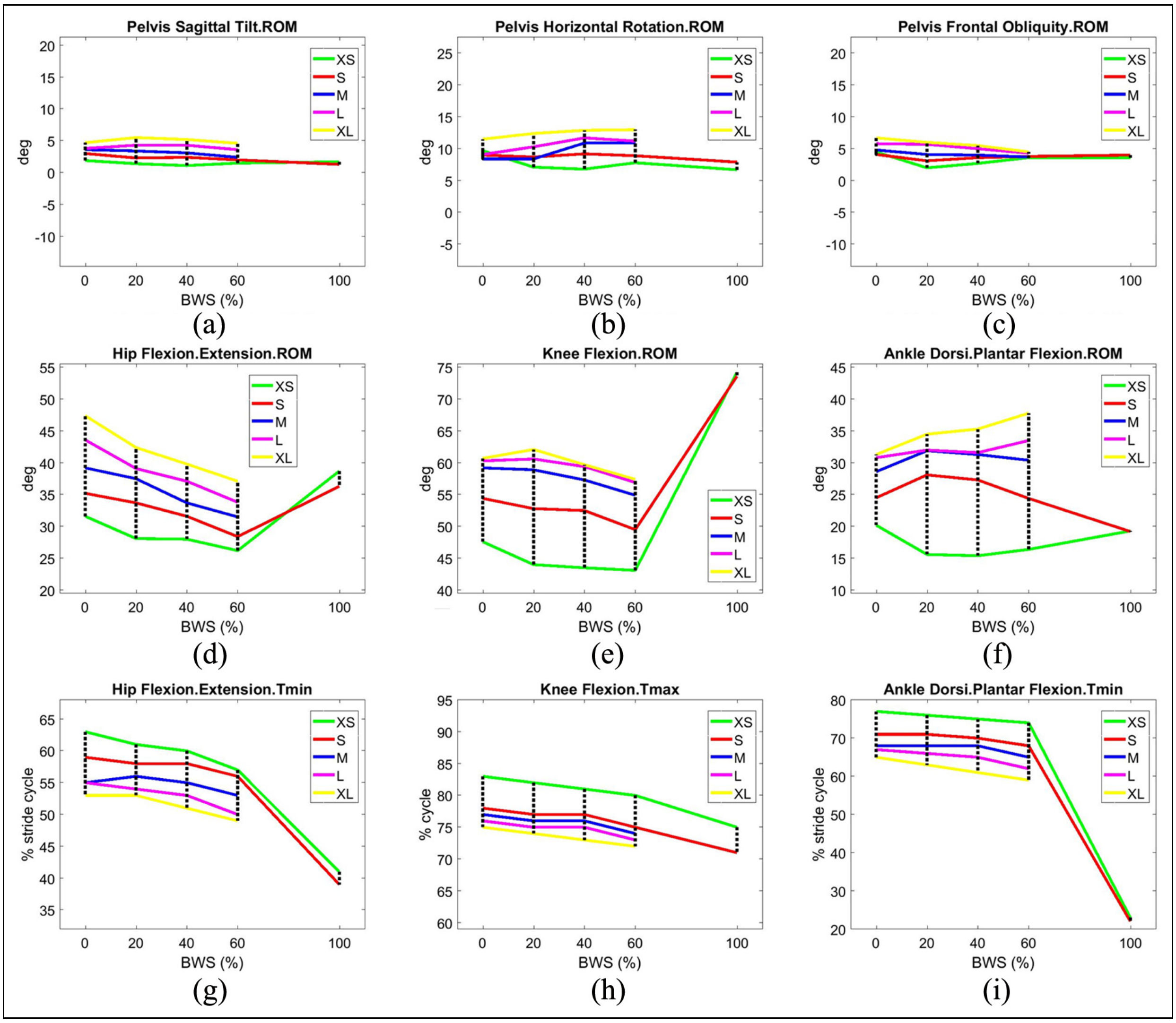

Figure 5. Modulation of amplitude (pelvis tilt (a), pelvis rotation (b), pelvis obliquity (c), hip (d), knee (e), ankle (f)) and temporal (timing of max hip extension (g), max knee flexion (h), max ankle plantar-flexion (i)) kinematic parameters induced by different amounts of BWS and gait velocities (color code as in Figure 3). Values are averaged among all subjects.

conditions, but air stepping, and concluded that this is likely because lower limb biomechanics has to be adjusted to natural interactions with the ground and the absence of contact events can disrupt normal phase control and trajectory formation in human locomotion.

On the other hand, the availability of angular displacements of the hip, knee, and ankle spontaneously produced by healthy people during on-air stepping are useful in the robotic rehabilitation of walking. Passive to progressively active exercises under full BWS seem to improve gait and functional ambulation in traumatic brain injured (TBI) patients with severe motor impairments.[16] Indeed, these patients are often impaired on both body sides and need to reacquire the locomotor body schema as well as postural awareness and stability. On-air stepping, according to physiological joint movements, could then represent a first phase of their rehabilitation, which could be reasonably followed by a progressive reduction of BWS in the subsequent training phases.

Another training environment able to facilitate motor activity in the early stages of rehabilitation is represented by water.[31] Underwater gait exercises can be used in specific rehabilitation trainings to make the most of full joint range of motion and to decrease the vertical component of the ground reaction force.[32] In recent years, underwater gait-training devices have been developed[33] to reproduce physiological gait patterns for aquatic exercises. The results of this study, investigating the amount of BWS on lower limb joints' kinematics during treadmill walking at different gait speeds, provide curves that could be of reference also for devices built to reproduce the physiological walk in water, with water depth adjusted so that body weight could be reduced to the desired amount.

It should be emphasized that children and elderly were not included in this study; therefore, the data presented here are well suited to patients of comparable age (range 23–48 years) and should be adopted with caution on geriatric and, even more, on pediatric populations. Future studies should explore the possible effect of age on these trajectories of weight-supported treadmill walking and, if necessary, consider age as additional parameter.

Conclusion

In conclusion, the findings of this study confirm, in a single well-controlled experimental setup, that lower limb kinematics during treadmill walking is affected both by gait speed and by the amount of BWS. When the body weight is fully supported, and thus subjects are stepping on air, the kinematics is very different due to the absence of ground contact and the associated driving mechanism of the treadmill on feet. Since the gait speed and the BWS level must be individually adjusted according to the rehabilitation phase and the residual locomotor abilities of the patient, the corresponding reference kinematics of the lower limbs must also be defined accordingly. In spite of that, the reference trajectories normally used by robotic devices to fulfill BWS walking training are typically taken from normative databases of overground unassisted walking. The numerical data experimentally collected in this study on healthy adults and included in the attached electronic addendum, provide normative data to be used as reference trajectories for controlling robot-assisted BWSTT at different gait speeds and levels of BWS.

Acknowledgements

The authors wish to thank Dr Francesca Garbarini, who has contributed to the acquisition of data, and all the subjects who voluntarily took part in the experiments.

Declaration of conflicting interests

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Funding

The author(s) disclosed receipt of the following financial support for the research, authorship, and/or publication of this article: This work was partially supported by funding from the Italian Ministry of Health (Fondi IRCCS Ricerca Corrente), who had no role in the study design, analysis of results, writing the manuscript, or in the decision to submit for publication.

Supplementary material

Supplementary material is available for this article online.

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