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Kinematic trajectories while walking within the Lokomat robotic gait-orthosis

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Abstract

Background One of the most popular robot assisted rehabilitation devices used is the Lokomat. Unfortunately, not much is known about the behaviors exhibited by subjects in this device. The goal of this study was to evaluate the kinematic patterns of individuals walking inside the Lokomat compared to those demonstrated on a treadmill.

Methods Six healthy subjects walked on a treadmill and inside the Lokomat while the motions of the subject and Lokomat were tracked. Joint angles and linear motion were determined for Lokomat and treadmill walking. We also evaluated the variability of the patterns, and the repeatability of measuring techniques.

Findings The overall kinematics in the Lokomat are similar to those on a treadmill, however there was significantly more hip and ankle extension, and greater hip and ankle range of motion in the Lokomat ($P < 0.05$). Additionally, the linear movement of joints was reduced in the Lokomat. Subjects tested on repeated sessions presented consistent kinematics, demonstrating the ability to consistently setup and test subjects.

Interpretation The reduced degrees of freedom in the Lokomat are believed to be the reason for the specific kinematic differences. We found that despite being firmly attached to the device there was still subject movement relative to the Lokomat. This led to variability in the patterns, where subjects altered their gait pattern from step to step. These results are clinically important as a variable step pattern has been shown to be a more effective gait training strategy than one which forces the same kinematic pattern in successive steps.

Keywords: Lokomat; Robotics; Gait; Kinematics; Rehabilitation

1. Introduction

In recent years, the field of neurorehabilitation has been adopting robotic devices to help deliver mass-practice therapy to individuals with various types of neurological disorders (see Hidler et al., 2005 for review). For applications targeting gait training, robotic devices present numerous potential advantages over therapist-assisted training, as these devices can deliver time-unlimited training sessions, and the parameters through which the subjects are trained can be accurately controlled (e.g. leg kinematics). Furthermore, the instrumentation on these devices makes it possible to quantify walking performance and track recovery in an un-subjective manner (Hidler, 2005).

While there are numerous gait training devices being used around the world, the Lokomat (Hocoma AG, Volketswil, Switzerland) is by far the most widely adopted system, where it is now being used by over 130 rehabilitation centers world-wide to treat patients following stroke, spinal cord injuries, traumatic brain injury, and multiple sclerosis. A number of small pilot studies have been evaluating the clinical benefits of Lokomat training. For example, following 12 weeks of Lokomat training, incomplete

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spinal cord injured subjects (ASIA C-D) demonstrated improvements in walking ability, endurance, and lower extremity function (Wirz et al., 2005). Similar effects have been reported in incomplete spinal cord injury (SCI) (Hornby et al., 2005) acute brain injured subjects (Mayr et al, 2002), and acute stroke (Husemann et al, 2007; Mayr et al, 2007).

In our previous work, we studied changes in muscle activation patterns in healthy individuals walking in the Lokomat when compared to walking on a treadmill (Hidler and Wall, 2005). It was found that in the quadriceps leg muscles, such as the rectus femoris and vastus lateralis, walking in the Lokomat resulted in substantially higher activation patterns while the gastrocnemius and tibialis anterior ankle muscles resulted in significantly less activity. We hypothesized that changes in muscle activation patterns were due to the reduction in degrees of freedom subjects experience while walking in the Lokomat. For example, it appeared that subjects were lifting their knees higher than normal in order to compensate for their inability to rotate the hips and the legs, behaviors needed to clear the foot during swing.

Unfortunately our characterization of leg kinematics were done only through visual observation and not quantified. No studies to date have tracked the kinematics of the legs inside the Lokomat, mainly because of the challenges standard passive motion capture systems face inside the device. For instance, there are a number of reflective surfaces on the Lokomat which often leads to false marker tracking. Also, because the Lokomat resides on the outside of the legs and is coupled to the subject through rear leg cuffs, only a portion of the front surface of the subject's legs is available for marker placement. Finally, markers are often occluded from camera view resulting in significant marker dropout throughout the gait cycle. Utilizing an active-based marker system (Codamotion, Charnwood Dynamics LTD, Rothley Leicestershire, UK), we have recently been able to overcome these limitations and successfully track leg kinematics inside of the Lokomat (Neckel and Hidler, 2006).

In parallel with the uncertainty of the leg trajectories exhibited by subjects while walking in the Lokomat is the amount of relative leg motion inside the device. That is, some propose that because the Lokomat is coupled to the subject's legs, there is little variability in the gait pattern throughout the training session. Some preliminary work with animals studies have suggested that training under a variable step pattern is more effective at improving step patterns than walking with a fixed, continuous step trajectory (Cai et al., 2005), so it would be advantageous to know how much the subject's leg moves within the Lokomat during a step sequence.

The goals of this study were four fold. First, we were interested in determining how the kinematic pattern subjects exhibit inside the Lokomat compare to those used while walking on a treadmill at similar speeds, in terms of both the shape and variability of the patterns. Second, we wanted to quantify the amount of relative motion occurring between the joint centers of the Lokomat and the subject. Since the ability of the Lokomat to assist a subject's leg through a prescribed kinematic pattern relies on the alignment of the subject's joint centers with those of the device, it is important to understand how joint alignment is maintained throughout the gait cycle. Third, since joint alignment and kinematic trajectories can be influenced by how well a subject is setup inside the Lokomat, were wanted to quantify the repeatability of kinematic trajectories over consecutive training sessions. And finally, it is possible that throughout training sessions, subjects adapt to the Lokomat and "learn" the prescribed kinematic trajectory. Therefore, our last goal was to determine how much motor learning and adaptation occurs when subjects walk inside the Lokomat when their initial kinematic patterns are compared to those at the end of the training session. These findings will help clinicians get a better sense of how subjects actually behave while in the Lokomat, and thus improve the quality of treatment. Portions of this work have been previously reported (Neckel et al., 2006).

2. Methods

2.1. Subjects

A total of six healthy subjects (4 male, 2 female) with no known neurological injuries or gait disorders participated in the study (mean age: 27 years; range: 21–33). All experimental procedures and risks were explained to each subject prior to their participation and approved by the Institutional Review Boards of Medstar Research Institute and the Catholic University of America.

2.2. Instrumentation

The Lokomat robotic gait-orthosis (Hocoma AG, Volketswil Switzerland) was the primary equipment used in this study. A full description of the device can be found at Colombo et al. (2000). Briefly, this system consists of a treadmill, a dynamic unloading system, and two lightweight robotic actuators that attach to the subject's legs. The hip and knee joints are actuated by small DC motors and linear ball screw assemblies. The kinematic trajectories of the Lokomat are fully programmable, and are adjusted to each individual's size and step preference. The complete device resides on a large parallelogram which is counterbalanced by a passive spring. The pretension in the spring is adjusted so that the weight of the Lokomat is compensated for, limiting upward or downward external forces to the subject during training.

A Codamotion active motion analysis system (Charnwood Dynamics LTD, Rothley Leicestershire, UK) was used to track the subject's pelvis and legs as well as the Lokomat pelvis, thigh and shank. Markers were grouped in clusters of four and placed on the anterior surface of each limb segment. Markers for the Lokomat pelvis, as well as the left and right thigh were fixed directly to the rigid plastic covers. Plastic extensions were firmly attached to the Lokomat shanks to provide a broader surface for attaching the marker clusters to the shanks. In order to track the motion of the subjects limbs while inside the Lokomat, custom marker clusters were designed so that the cuffs that fix the subject to the Lokomat would not interfere with the placement of markers. First, rigid plastic bases with thin foam undersides were slipped under the Lokomat leg cuffs. These bases were firmly attached to the subject's leg using the Lokomat cuff strap, as well as additional hook and loop straps wrapped around the subject's limb segment. The motion tracking marker clusters were attached to the plastic bases with hook and loop straps. Finally, the transmitter boxes of the Codamotion tracking system were secured with self-adherent Coband compression tape wrapped around the limb segment, providing additional support to the tracking marker clusters. The Codamotion camera was placed approximately 1 m in front of the Lokomat which resulted in a marker tracking accuracy of 1 mm (based on factory testing).

An ADAL split-belt treadmill (Tecmachine, Andrezieux Boutheon France), which contains eight Kistler tri-axial force sensors (Winterthur, Switzerland), four per half-treadmill, was used during both treadmill walking and Lokomat walking. The ADAL allows for ground reaction forces to be recorded for each step of either leg, providing markers for breaking up each trail into individual strides.

2.3. Protocol

After donning specialized footwear (adjustable leather moccasins) each subject first walked on the treadmill without the aid of the Lokomat for a few minutes in order to get used to walking on the treadmill. After this acclimation phase, each subject walked at four different walking speeds (2.0, 2.4, 2.8, and 3.2 km/h) three separate times for a total of 12 trials. The order was randomly selected in order to eliminate any bias associated with the order in which speeds were tested. Each speed was recorded from before repeating speeds. With each change in treadmill speed, the subject walked for a 1 min acclimation phase, after which marker positions and ground reaction forces were recorded for 30 s step sequences.

Following the treadmill trials, the subject was allowed to sit down as the standard marker clusters were removed and the custom Lokomat marker clusters were attached. The subject was then led into the Lokomat, and with the help of an experienced physical therapist who has used the Lokomat for over 3 years, the device was adjusted so that the Lokomat hip and knee centers lined up with the joint centers of the subject. To reduce the variability of the setup, the same physical therapist was used throughout the experiment, for every experiment. After being firmly strapped in, the subject walked at a comfortable pace (2.4 km/h) and the physical therapist adjusted the step length of the Lokomat until the subject felt comfortable with the gait pattern. As with standard clinical practice the Lokomat was run in a position control mode with 100% guidance force, where the legs of the Lokomat move through a strict pre-determined gait pattern (adjusted on a subject-by-subject basis) and the subjects were instructed to match the pattern. After just a short acclimation period (e.g. less than 2 min), all subjects reported that walking in the device felt comfortable and the kinematic trajectory was easy to follow.

Each subject was first allowed to walk in the Lokomat for up to 5 min in order to acclimate to the device and for the therapist to make minor adjustments (e.g. tighten leg cuff straps, optimize joint alignment, alter gait trajectory). After this acclimation period, the Lokomat walking speed was randomly set to one of the four speeds used during treadmill ambulation, and after a 1 min acclimation phase, marker positions and ground reaction forces were recorded for 30 s step sequences. This same procedure was repeated three times for all four speeds (2.0, 2.4, 2.8, and 3.2 km/h), resulting in a total of 12 trials. It should be noted that this speed range was selected since the Lokomat best operates over these conditions, and has a top speed of 3.2 km/h, even though normal overground walking speeds are in the 4.5–4.9 km/h range (Himann et al, 1988).

2.4. Analysis

The Codamotion marker positions were recorded at 100 Hz and exported to the software package Visual 3D (C-Motion INC, Rockville MD) where a subject-specific model of each subject along with the subject's Lokomat configuration was created from subject anthropometric data and known Lokomat dimensions. Using this 3D model, ankle, knee and hip joint center locations and limb angles were estimated. Even though the active marker system reduced the number of missing markers, there was still the occasional missing marker. These missing marker points were interpolated with a third order polynomial before being exported to the software package Matlab (Mathworks, Natick MA) where the signals were filtered with a fourth order Butterworth filter with a cutoff frequency of 20 Hz. Ground reaction forces were recorded at 1000 Hz and similarly filtered in Matlab. Individual stride cycles were determined for each 30 s trial using the vertical ground reaction force data, where each stride was considered the period between successive heel-strikes in the same leg (Hidler and Neckel, 2006). All kinematic data was then time normalized, expressed as a percentage of the total gait cycle (i.e. 0–100%) and re-sampled to 5 kHz for averaging purposes. All kinematic measures were calculated for each stride and then pooled and averaged to produce the value for each speed tested.

2.4.1. Kinematic analysis

The angular range of motion (ROM) in the sagittal plane for the hip, knee, and ankle was found by subtracting the minimum joint angle from the maximum joint angle for

Lokomat and treadmill trials at each walking speed. Peak ankle flexion and extension, knee flexion and hip flexion and extension were also identified for each trial. These values, and the phase of the gait cycle in which they occurred, were used to evaluate the kinematic differences between treadmill and Lokomat walking. A t-test was used to test for differences greater than 3° or 3% gait cycle in each of the dependent measures, using an alpha level of 0.05. We tested for differences greater than 3° since our motion tracking accuracy was determined to be within this range.

To investigate the movement constraints a subject experiences while walking inside the Lokomat, the knee and hip joint x–y–z positions of the subject were tracked in both the frontal and sagittal planes for both walking modalities. Since subjects are not restricted to walk at a particular location during the treadmill portion of the study, their mean x (e.g. medial–lateral) and y (e.g. anterior–posterior) positions in lab space may be quite different than those while walking in the Lokomat. For example, subjects may ambulate on the treadmill slightly left and forward relative to the center of the treadmill. In order to align the different joint center trajectories, the mean x and mean y locations of the joints were removed from each trajectory, leaving relative motion.

We also compared the x–y–z positions of each subject's knee and hip joints with respect to the positions of the Lokomat joint centers to determine how much relative leg movement occurs while walking inside the Lokomat. This would provide some indication of how much misalignment occurs between the subject and the device throughout the gait cycle. Normative error between the Lokomat and subject's joint centers was calculated across the gait cycle as:

$$\text{Error} = \sqrt{(X_{\text{Lokomat}} - X_{\text{Subject}})^2 + (Y_{\text{Lokomat}} - Y_{\text{Subject}})^2 + (Z_{Lokomat} - Z_{\text{Subject}})^2} \quad (1)$$

2.4.2. Repeatability

One subject was tested on three separate occasions to check the reliability of the modeling techniques used in Visual 3D and to measure the repeatability of subject setup inside of the Lokomat robotic orthosis. Mean ankle, knee and hip angles in the sagittal plane were determined for each of the training sessions across speeds, and compared using a multi-factor ANOVA.

2.4.3. Motor learning in the Lokomat

To determine whether subjects adapt and "learn" to walk like the Lokomat, the average ankle, knee, and hip angles of the first 10 steps of the first trial were compared to the average ankle, knee, and hip angles of the last 10 steps of the last trial at that same speed.

3. Results

3.1. Lokomat versus treadmill kinematics

Fig. 1 illustrates the ankle, knee and hip angular trajectories for one representative subject while walking on the treadmill and in the Lokomat for the same speed. When the measurements from all subjects were pooled together, significant differences between Lokomat and treadmill walking were found. For the ankle, the same general trajectory is produced during both walking conditions however, the range of motion and maximum ankle extension is greater in the Lokomat ($P < 0.05$). Additionally, we found that peak ankle flexion occurred 11.7% earlier in the gait cycle, where the mean peak flexion angle occurred at 42.4% and 54.2% of the gait cycle for the Lokomat and treadmill respectively. For the knee, no statistical differences were found for knee range of motion, peak flexion angle, or the percent of the gait cycle in which this peak occurs. The hip angles for the Lokomat and treadmill were similar, however, the range of motion and maximum hip extension was greater when subjects walked in the Lokomat compared to when they walked on the treadmill ($P < 0.05$). Similar to the ankle, the percent of the gait cycle where peak hip extension occurred was earlier in the Lokomat than on the treadmill, implying the subjects began initiating swing earlier when walking in the Lokomat. No differences were found for peak hip flexion or the phase of the gait cycle in which it occurred. The kinematic values for treadmill and Lokomat walking are summarized in Table 1.

In addition to the joint angles described above, we also looked at the X–Y–Z joint paths of the ankle, knee, and hip for treadmill and Lokomat trials in both the frontal and sagittal planes. An illustrative example of the mean sagittal plane trajectories for a single subject is shown in Fig. 2. The ROM at the ankle is significantly larger in the Lokomat than on the treadmill ($P < 0.05$), a strategy we believe is used to help clear the foot during swing. That is, since the subjects cannot weight shift to the contralateral limb and rotate the hips during swing, in order to clear the foot during swing, the subject must lift their foot to a greater extent. For the knee, there were no differences between the two walking conditions (Fig. 2B). The hip motion in the Lokomat was found to be significantly less in the anterior–posterior plane (e.g. y-axis), mainly due to the fact that the device stabilizes the subject's hips, preventing the natural rotation observed on the treadmill. As a result,

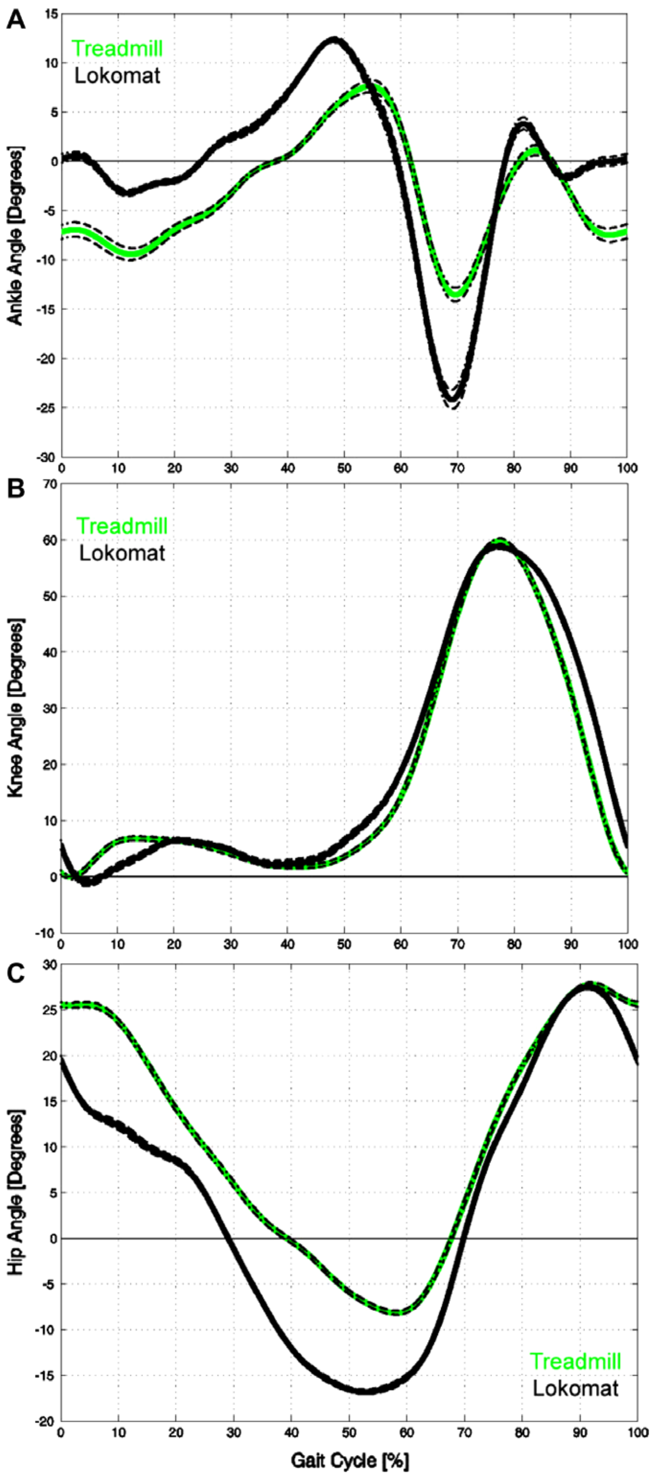

Fig. 1. Ankle (A), knee (B), and hip (C) joint angles during Lokomat and treadmill walking of a representative subject (Lokomat: dark trace; Treadmill: light trace). For all joints, flexion is positive, extension is negative. Dashed lines represent 95% CI.

the only true degree of freedom at the hip is in the vertical plane.

In the frontal plane, the most striking difference between walking in the Lokomat versus walking on the treadmill is the reduction in the medial–lateral motion, particularly at the hip. Because the device is secured firmly to the hips and prevents side-to-side motion, the ability to rotate the hips is limited. For treadmill ambulation, subjects can rotate and list their hips, weight shift between legs, and can slightly circumduct the leg, characteristics necessary to clear the foot during swing. These characteristics are illustrated in Fig. 3 where it can be seen that for the treadmill trials, there is significantly more medial–lateral motion, particularly at the hip whereas in the Lokomat, the joint centers move through a greater vertical range. The small amount of medial–lateral hip movement observed for Lokomat walking is mainly due to the padded hip bumpers compressing, while a small amount can be attributed to the flexing of the parallelogram structure supporting the device.

We did not find that any differences between the Lokomat and kinematic trajectories were speed dependent, as the same relationships between the two walking conditions mirrored each other across the four speeds tested.

Table 1
Kinematic metrics in the sagittal plane for Lokomat and Treadmill walking

	Treadmill		Lokomat	
	Angle	% Gait cycle	Angle	% Gait cycle
Hip min	−9.06 (2.77)	58.54 (0.87)	−16.15 (4.59)[a]	53.83 (2.33)[a]
Hip ROM	38.73 (5.45)		45.66 (3.03)[a]	
Knee max	63.13 (5.84)	77.35 (1.9)	61.24 (3.99)	76.76 (1.57)
Knee ROM	63.4 (6.4)		60.29 (3.61)	
1st Ankle min	−9.69 (2.38)	11.07 (1.26)	−6.62 (2.67)	9.91 (1.87)
Ankle max	8.04 (3.72)	54.17 (2.94)	8.79 (2.71)	42.39 (10.62)[a]
2nd Ankle min	−9.61 (5.12)	68.52 (1.97)	−17.99 (7.83)[a]	65.46 (3.07)
Ankle ROM	20.74 (3.88)		29.2 (6.16)[a]	

SD in parenthesis.
[a] Different from Treadmill ($P < 0.05$).

3.2. Misalignment of joint centers

The ability of the Lokomat to assist the subject's legs through a specific kinematic pattern relies heavily on the alignment of the individual's joint centers with those of the device. As such, we were interested in seeing how much relative movement occurs throughout the gait cycle inside the device. Fig. 4 illustrates the normative error (Eq. (1)) between the Lokomat and subject's knee and hip joint centers. It can be seen that for the knee, misalignment tends to be the greatest during swing, often more than 2 cm. For the hip joint, misalignment increases progressively during stance, often reaching 4 cm. This misalignment can be explained by referring to Figs. 2a and 3. During normal treadmill ambulation, the subject rotates their hips significantly throughout stance phase in order to help the contralateral limb clear the foot during swing. While the

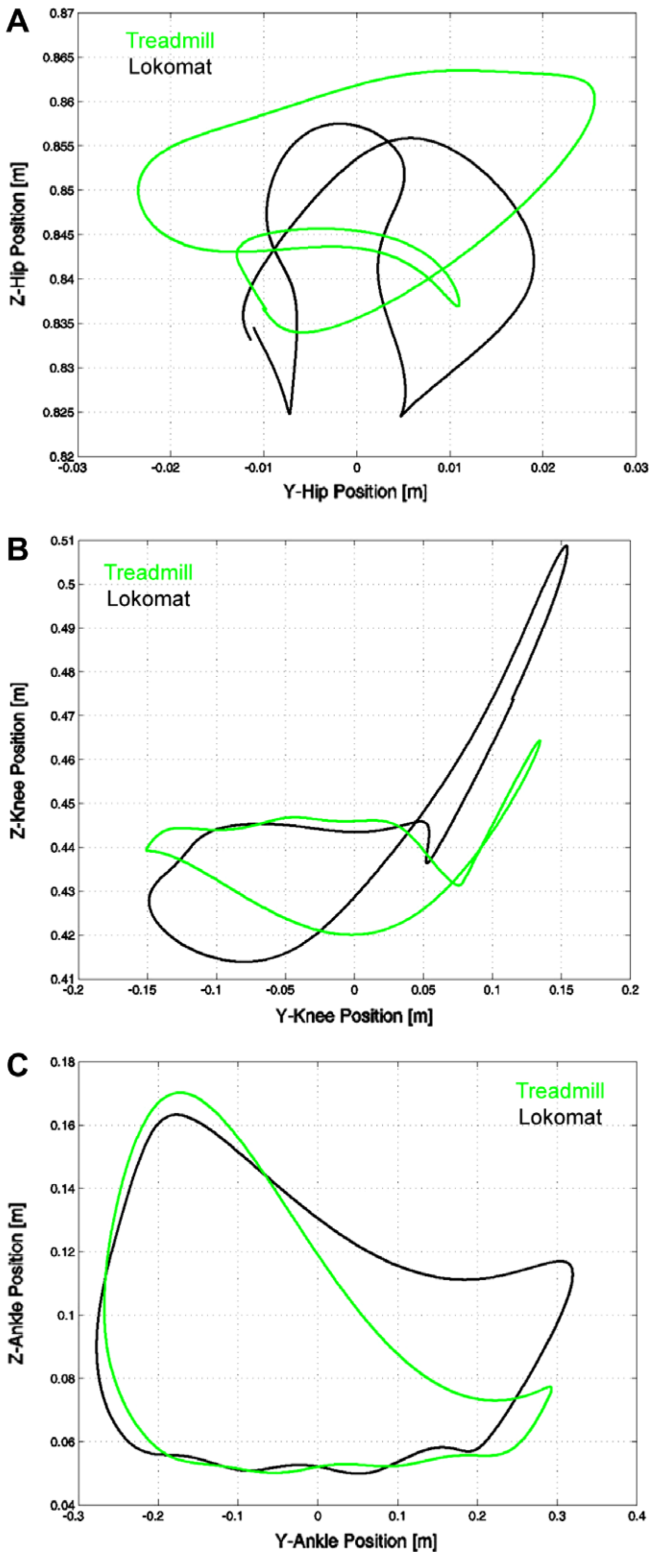

Fig. 2. Cartesian position (*X*–*Y*–*Z*) of a representative subject's ankle, knee, and hip joints for Lokomat and treadmill ambulation in the sagittal plane (Lokomat: dark trace; Treadmill: light trace).

Lokomat restricts the subject's hips in anterior–posterior and medial–lateral axes, the subjects appear to still attempt this normal motion which leads to the hip misalignment.

3.3. Repeatability of measures

One subject was tested on three separate occasions in an attempt to determine whether the subject setup in the Lokomat, or the Visual 3D anatomical modeling done to estimate joint angles, were dependent on how the tracking markers were affixed to the subject or how the subject was setup in the device. Interestingly, we found no differences in the kinematics across the three sessions. The maximum difference between any of the three trials for all metrics tested was less than 3° of angular difference or 3% of phase difference in the gait cycle, values slightly greater than our accuracy limits.

3.4. Learning effects of walking in the Lokomat

Since the subjects tested in this study had no known gait deficits, we were interested in how they may adapt to walking in the Lokomat, effectively changing their kinematic pattern to that of the Lokomat. The instructions to the subject during the testing were only to walk in the Lokomat so that you feel comfortable; no other explicit instructions were given. Comparing the first 10 strides of the very first trial to the last 10 strides of the last trial run at the same speed, it was seen through visual inspection that no adaptation occurred during the test session. We estimate that each subject took approximately 500 steps over more than 20 min between comparisons, at a variety of speeds, which should have resulted in changes in the motor program (Shadmehr and Mussa-Ivaldi, 1994) or differences in leg kinematics (Gordon and Ferris, 2007). It appears that all of the adaptations to the Lokomat occurred within the first 5 min of the pre-testing phase where subjects were allowed to walk in the device prior to data collection.

4. Discussion

The goal of Lokomat gait training is not to replicate the exact kinematic trajectories subjects exhibit during treadmill ambulation but instead to help subjects achieve a natural gait pattern. Previous research has suggested that, from a rehabilitation perspective, treadmill walking patterns are similar to overground walking patterns (Lee and Hidler, 2008). Our results indicate that when subjects walk in the Lokomat, their ankle, knee, and hip angles follow patterns that upon visual inspection are similar to patterns found when they walk on the treadmill. While at the same time, there is some kinematic freedom to explore their workspace as evidenced by the relative hip and knee movement within the Lokomat. Even though statistically significant differences were found in specific kinematic measures (see Section 3.1), it is questionable whether the observed differences are large enough to be clinically significant. While the Lokomat may change the healthy hip ROM by almost 7°, this may be of little concern to a patient whose hip ROM is severely impaired by injury.

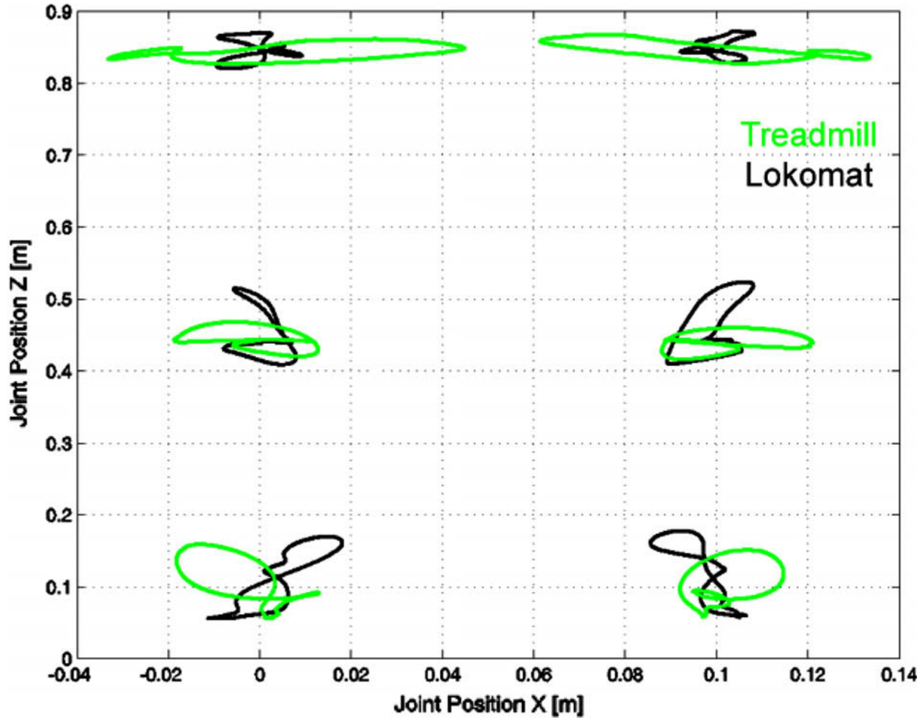

Fig. 3. Joint center motion for the subject's hips (top), knees (middle), and ankles (bottom) during treadmill and Lokomat walking in the frontal plane. Note the significant decrease in medial–lateral motion of the hip in the Lokomat (dark trace) compared to the treadmill (light trace).

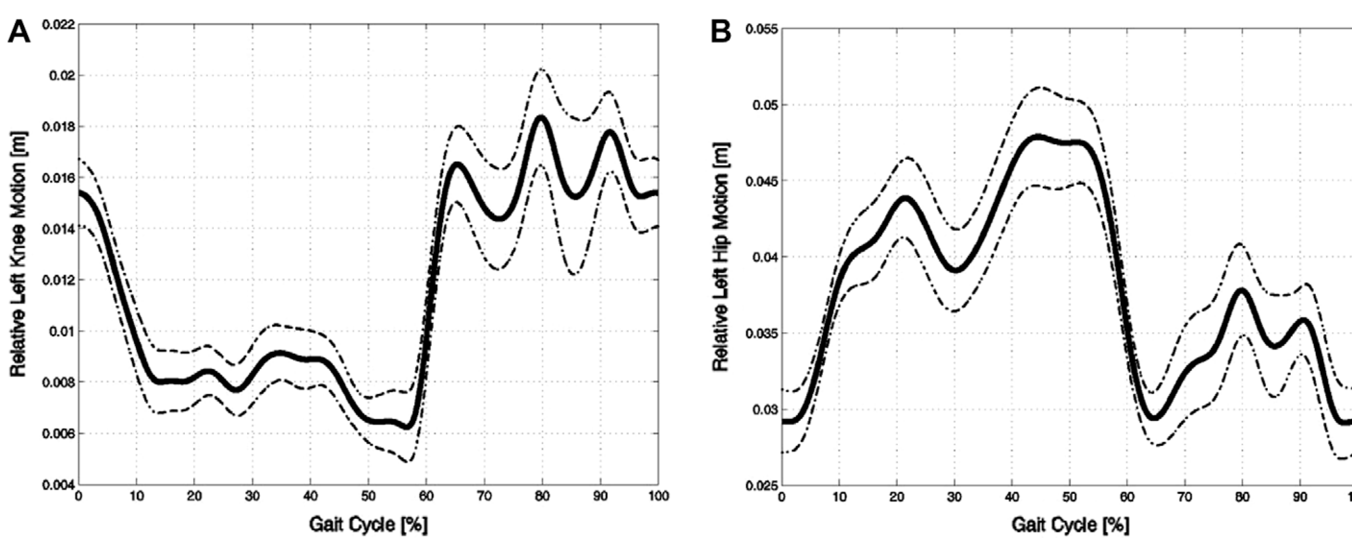

Fig. 4. Average knee and hip joint alignment errors between the subject and Lokomat across the gait cycle, for all subjects. For the knee (A), misalignment is greatest during swing while for the hip (B), and maximum joint misalignment is greatest during late stance. Dashed lines represent 95% CI.

The changes in kinematic patterns we observed may be explained by the restrictions the Lokomat places on the subject. For example, it was shown in Fig. 3 how little the medial–lateral movement subjects exhibit at the hip when walking in the Lokomat. Rather than the pelvis rotating posteriorally during stance, the pelvis remains relatively fixed causing the leg to be drawn into further extension (Fig. 1C). To compensate for this, subjects appear to adopt two strategies. First, at the end of stance, hip flexion occurs at a much higher rate in the Lokomat in order to get the foot high enough to clear the floor during swing (note the significant difference in slopes for the Lokomat and treadmill hip kinematic trajectories between 60–80% of the gait cycle, which is early to mid swing. See text for explanation). This is consistent with the changes in EMG patterns we observed in our previous study where there was elevated activity in the Rectus Femoris during early to mid swing when subjects walked in the Lokomat (Hidler and Wall, 2005). The second compensatory strategy used to overcome pelvic restrictions is the magnitude of ankle extension is higher in the Lokomat, and the point in the gait cycle in which subjects begin to extend their ankle comes earlier in the gait cycle, sometimes by more than 10%. Combined, these two strategies would help ensure the toe clears during swing.

4.1. Variability in step patterns

One clinical concern that is often raised with Lokomat gait training is the lack of variability in the gait patterns. It is believed that because the system is often run with 100% guidance force, meaning the Lokomat attempts to enforce a particular gait pattern regardless of the subject's intentions, subject's lack the ability to vary their kinematic patterns from step to step. We found that subject's did have the ability to alter their gait in the Lokomat, which is evidenced by the variability around the knee and hip misalignment shown in Fig. 4. This 'freedom' is presumably caused by the non-rigid coupling of the subject to the Lokomat. Velcro straps are used to fasten the subject's legs into carbon-fiber cuffs, which have some inherent flexibility. Additionally, the hip pads that secure the subject's medial–lateral motion are soft and have some compressibility. Combined, this non-rigid coupling allows the subject to alter their gait pattern during successive steps.

A recent animal study compared the recovery of locomotor patterns in spinalized mice that underwent either a fixed kinematic training trajectory or a variable kinematic trajectory, both using a robotic gait trainer (Cai et al., 2005). It was found that mice trained with variable step patterns showed higher levels of recovery, in terms of the number of steps they could take during evaluation sessions, and their step periodicity and shape consistency was higher. While recovery patterns of rodents may not be representative of those found in humans, these findings suggest variable gait patterns might be advantageous.

4.2. Limitations with study

One of the primary limitations with this study is that the kinematics of the Lokomat are adjustable, including hip and knee ROM and the offset angle in which the entire trajectory can be shifted (e.g. maintain ROM, shift entire trajectory into flexion or extension). Our results are based solely on the kinematic pattern we chose for each subject, which was adjusted until the subject felt comfortable and was walking close to their "true" overground gait. It may have been the case where a different trajectory would have resulted in a better match between treadmill and Lokomat kinematic patterns. However, the aim of this study was to investigate kinematic variations found in the clinical setting, and the gait pattern chosen here was found using the same procedures followed in the clinic. Utilizing the experience of the clinical staff, the initial chosen trajectory is based on the subject's height and range of motion at the joints (e.g. less hip extension when tight hip flexors are present). We then ask the subject how they feel during the first training session and change the kinematics until they feel comfortable and are able to reproduce a consistent step cycle. For healthy subjects, we could in theory best match their natural gait cycle by continuously adjusting the Lokomat, however for individuals who cannot ambulate without assistance, this technique would not be possible.

A second limitation with this study is that the guidance force of the Lokomat was always set to 100%, meaning the device is setup to be a stiff servo. New control algorithms for the Lokomat allow the system to be run in an impedance mode, where the device can offer varying levels of assistance. We believe this mode would clearly result in differences in the kinematics and variability estimates we found in this study. Since most patients are run with high guidance force (near 100%) and only the small percentage that make significant improvements in walking ability can be lowered down to minimal robot assistance, testing under conditions most representative of clinical training seemed appropriate.

Another potential limitation with the study is the fact that only young, healthy subjects with no gait impairments were tested in this study. It is possible that individuals with significant gait impairments may demonstrate more variability, or perhaps more likely, less ability to 'learn' the Lokomat trajectory. While these are distinct possibilities, studying these behaviors in healthy individuals provides a best case scenario for which patients receiving treatment can strive for. Doing similar comparisons on pathological patients would be impossible because collecting unassisted, or 'natural', kinematic patterns is often not possible.

4.3. Future application of results

The techniques and results presented here have direct bearing on future experimental and clinical uses of the Lokomat. The fact that subjects demonstrate significant motion while walking inside the Lokomat, in terms of movement of their legs with respect to the Lokomat, is extremely important for future experiments that attempt to quantify behavior within the Lokomat. And now knowing the extent to which the Lokomat restricts the movement of the pelvis may modify clinical treatments where weight shifting, arm swing, etc., are all needed to improve overground gait.

Conflict of interest statement

The authors declare that they have no competing interests.

Authors contributions

Nathan Neckel designed the experiment, carried out the experiments, and collected the data. Wessel Wisman carried out the experiments, collected, and analyzed the data. Joseph Hidler analyzed the data and drafted the manuscript. All authors read, edited, and approved the final manuscript.

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