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Limb Alignment and Kinematics Inside a Lokomat Robotic Orthosis

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Abstract- **The use of robotic gait training systems has become commonplace world-wide. In particular, the Lokomat robotic orthosis (Hocoma AG, Volketswil, Switzerland) is in use at nearly 75 facilities treating patients with spinal cord injury, stroke, and other neurological impairments. Despite the extensive use of the device, no studies have reported the leg kinematic trajectories while walking in the device. Furthermore, because the subject's legs are not rigidly coupled to the device, there is the potential for significant leg movement inside the device which also has not been reported. Here we report differences in kinematic trajectories between walking in the Lokomat and walking on a treadmill, as well as the relative limb motion within the Lokomat for a single representative subject. Using high-speed motion analysis, it was found that while similar knee and hip angle patterns were produced when walking on the treadmill and while walking in the Lokomat, there were significant differences (p<.01) in percent time spent in swing phase, maximum hip and knee flexion, and maximum hip extension. There was also a larger amount of misalignment at the hip (18.2mm) than at the knees (12mm) when the joint positions in space were compared.**

***Keywords*- Lokomat, gait, motion capture, robotics**

1. INTRODUCTION

The Lokomat (Figure 1; Hocoma AG, Volketswil, Switzerland) is a robotic orthotic device that provides variable body-weight support and ambulates a subjects lower limbs as they walk over a treadmill. Such body-weight supported locomotion therapy has shown promising results [1], even when compared to standard physiotherapy [2],[3].

Unfortunately, quantifying the interactions between the Lokomat and the subject has proven difficult. Even though the subject is firmly strapped into the device about the hip, thigh, and shank, there is some subject movement relative to the device. This becomes problematic if accurate gait analysis and inverse dynamic techniques are to be used to study subjects as they walk with Lokomat assistance.

As with standard gait analysis, motion tracking systems can be used to quantify the positions of the limb segments. However, some unique obstacles must be overcome to accomplish this with subjects inside the Lokomat. The reflective metal surfaces of the Lokomat make using passive reflective marker tracking systems difficult. Additionally, the cuffs that strap the subject to the device limit the area where tracking markers can be rigidly attached to the subject. And lastly, the simple fact that the Lokomat limbs obscure the view of the subject's limbs makes camera placement a challenge.

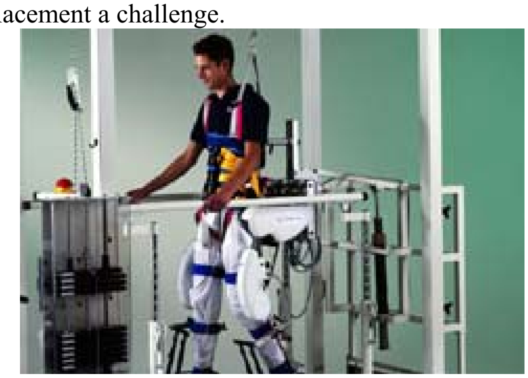

Figure 1. Lokomat robotic-orthosis (Hocoma, Inc., Zurich, Switzerland)

By using an active marker motion tracking system and custom marker clusters we can model the lower limb kinematics of subjects as they walk with the assistance of a Lokomat robotic orthosis. With this data we can also quantify the amount of movement and misalignment a subject experiences as they walk within the Lokomat.

Presented here are the lower limb kinematics of a healthy adult male as he walked at a comfortable speed of 3.2 km/h inside a Lokomat robotic orthosis. Misalignment inside the Lokomat was found by comparing hip and knee joint locations in the sagittal plane, along with differences in sagittal plane hip and knee angles. Lokomat walking kinematics were also compared to normal treadmill walking at the same speed.

2. METHODS

2.1 Instrumentation

A Codamotion active marker system (Charnwood Dynamics LTD, UK) was used to track the limbs of both the subject and the Lokomat. Motion tracking markers were grouped in clusters of four and placed on the anterior surface of each limb segment (Figure 2). 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 greater surface area before attaching the marker clusters.

In order to track the motion of the subjects limbs 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 (see Figure 2). First, rigid plastic bases with foam undersides were slipped under the Lokomat leg cuffs. The motion tracking marker clusters were then fixed to rigid plastic caps that would firmly fit on top of both the base and Lokomat leg cuff strap with hook and loop tape.

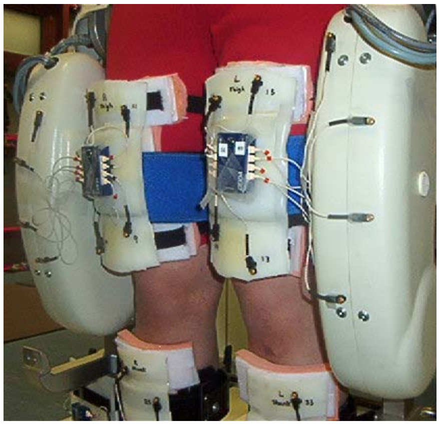

Figure 2. Active tracking markers placed on the Lokomat and custom marker clusters.

The Codamotion camera was placed approximately 2 meters in front of the Lokomat. An ADAL split-belt instrumented treadmill (Medical Development, France) was used below the Lokomat which allowed for ground reaction forces to be recorded for each separate step of either leg.

2.2Experimental Protocol

The subject was led into the Lokomat and with the help of a physical therapist the device was adjusted so that the hip and knee centers lined up with those of the subject. After being firmly strapped in, the subject walked at a variety of randomly selected speeds ranging from 1.5 km/h to 3.2 km/h in accordance with a different experimental protocol. After being acclimated to the selected speed, a 30 second long trial was recorded. In total, three trials at 3.2 km/h were recorded. Throughout the experiment the subject was asked to identify which speed they felt was the most comfortable and most like their normal walking speed. In the case of this subject, a speed of 3.2 km/h was selected as the most comfortable velocity.

Following the Lokomat walking experiment the subject was re-fitted with marker clusters designed for normal motion capture experiments. The same protocol of walking at randomly selected speeds was conducted on the treadmill outside of the Lokomat. Again, a total of three 30 second trials at 3.2km/h were collected.

2.3 Signal Processing

The marker positions were recorded at 100Hz and exported to the software package Visual3D (C-Motion INC, Rockville MD) where a customized model of both the subject and Lokomat limbs was created from subject anthropometric data and known Lokomat dimensions. From this model joint centers and limb angles were derived and exported to the software package Matlab (Mathworks, Natick MA) for filtering (Butterworth) and custom processing.

Ground reaction forces were recorded at 1000Hz and similarly filtered in Matlab. This data was used to mark the heel strike of each step, measured as a threshold of 50N of ground reaction force. Custom Matlab algorithms were used to breakup the 30 second trials into individual steps (from heel strike to heel strike) which were then resampled to the same signal length.

2.4 Kinematic Analysis

In the sagittal plane hip and knee joint offsets were calculated from the norm of the vector difference between Lokomat joint center position and the corresponding subject joint center position throughout the gait cycle for each step. To compare the amount of relative movement within the Lokomat, a trace of the hip and knee joint centers in space over the mean gait cycle were constructed. These traces were centered on their respective mean positions and overlaid. In the sagittal plane knee and hip angles were found for both the Lokomat and subject by pooling the right and left steps together.

To compare Lokomat walking with treadmill walking knee and hip angles were derived in a similar fashion of pooling the right and left sides. The additional metrics of maximum knee angle, maximum hip angle and minimum hip angle were compared using a single factor ANOVA.

3. RESULTS

Over the mean gait cycle the sagittal offset between Lokomat and subject left hip positions varied from 7.4mm to 19.8mm for a mean of 12.7mm. The right hip position varied from 6.3mm to 29.5mm for a mean of 18.2mm. The hip offset over the gait cycle can be seen in Figure 3 along with a trace of the mean left hip positions.

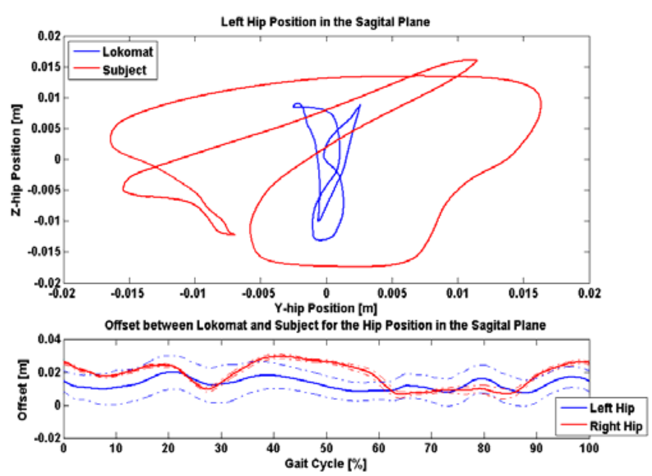

Figure 3. Top-Trace of Lokomat and subject left hip in space. Bottom- Lokomat and subject offset of left and right hip +/-STD

Over the mean gait cycle the sagittal offset between Lokomat and subject left knee positions varied from 6.1mm to 25.4mm for a mean of 12mm. The right knee position varied from 2.7mm to 19.5mm for a mean of 10.3mm. The knee offset over the gait cycle can be seen in Figure 4 along with a trace of the mean left knee positions.

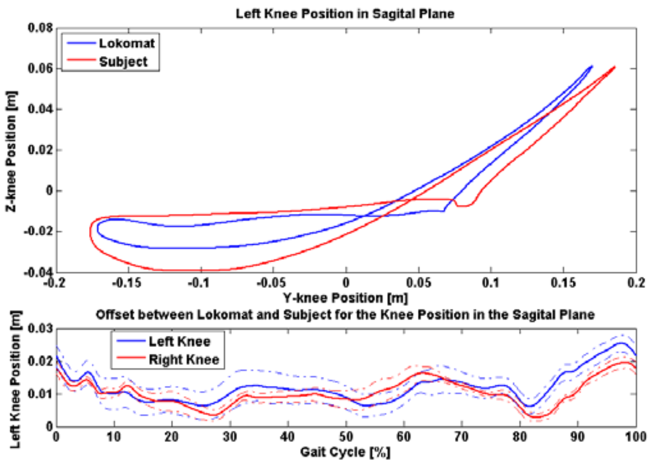

Figure 4. Top-Trace of Lokomat and subject left knee in space. Bottom-Lokomat and subject offset of left and right knee +/- STD

Figure 5 shows the mean knee angle and Figure 6 shows the mean hip angle of the subject as they walked in the Lokomat as well as when they walked on the treadmill at the same speed of 3.2 km/h. The maximum knee flexion on the treadmill was 65.04 degrees while the maximum knee flexion angle in the Lokomat was a significantly lower 60.76 degrees ($p<0.001$). The maximum hip flexion on the treadmill was 36.48 degrees while the maximum hip flexion angle in the Lokomat was a significantly lower 25.31 degrees ($p<0.001$). The maximum hip extension on the treadmill was 13.19 degrees while the maximum hip extension angle in the Lokomat was a significantly greater

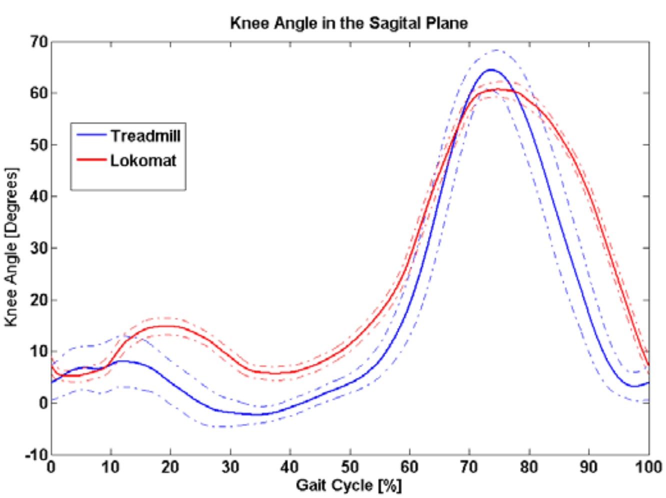

Figure 5. Knee angles in both normal treadmill and Lokomat walking +/- STD

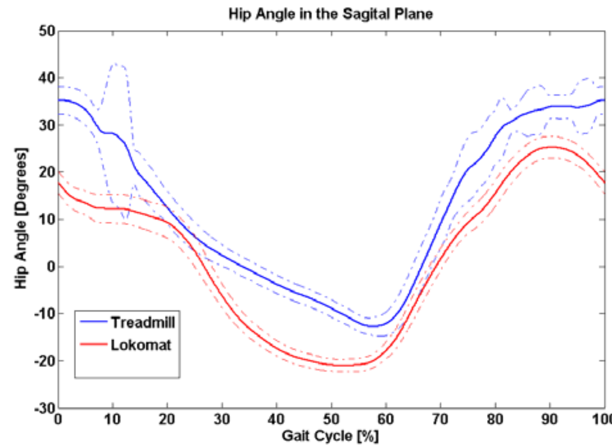

Figure 6. Hip angles in both normal treadmill and Lokomat walking +/- STD

21.11 degrees ($p<0.001$). The amount of time a limb spent in swing phase as a percent of gait cycle was 39.55 % on the treadmill and significantly lower in the Lokomat (38.97s; $p<0.001$). These metrics are shown in Figure 7.

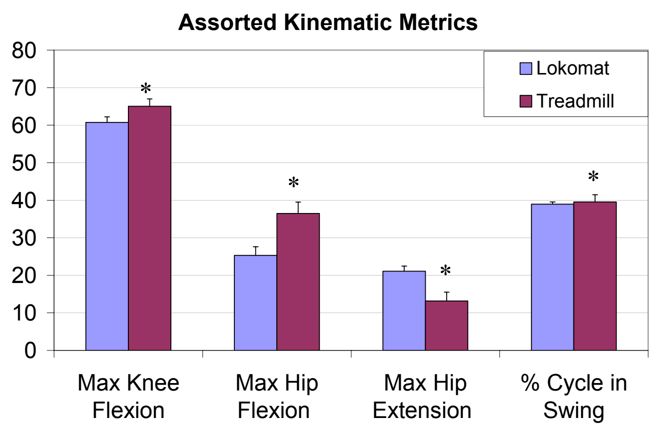

Figure 7. Kinematic metrics of Lokomat and normal Treadmill walking +/- STD. * - $p<.001$.

4. DISCUSSION

The results illustrate that the joint centers are never perfectly aligned, which one would not expect, but the surprising result is the difference between the right and left sides. For the knees this difference in offsets is not that concerning since it could have been the simple fact of one limb being better aligned and more firmly strapped in than the other. The fact that the offset follows a similar pattern and the left knee position follows similar traces is an encouraging sign that the Lokomat and subject knees are moving in similar patterns. The offset between the left and right hip is a bit surprising. The left hip was highly variable whereas the right hip was much less variable but more misaligned, and the offsets did not follow similar patterns. This suggests that the subject and the Lokomat hips were not following similar gait patterns. Further testing is needed to determine if this difference was due to the subject being poorly strapped in or the inability of the Lokomat pelvis to rotate. While the metrics in Figure 7 do demonstrate differences between Lokomat and treadmill walking, the overall gait patterns between the two gait modalities are similar.

5. CONCLUSION

Using high-speed motion analysis, it was found that while similar knee and hip angle patterns were produced when walking on the treadmill and while walking in the Lokomat, there were significant differences ($p<.001$) in percent time spent in swing phase, maximum hip and knee flexion, and maximum hip extension. There was also a larger amount of misalignment at the hip (18.2mm) than at the knees (12mm) when the joint positions in space were compared.

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