Inverse dynamics of split-belt locomotor adaptation in low and high effort conditions: an analysis on healthy individuals

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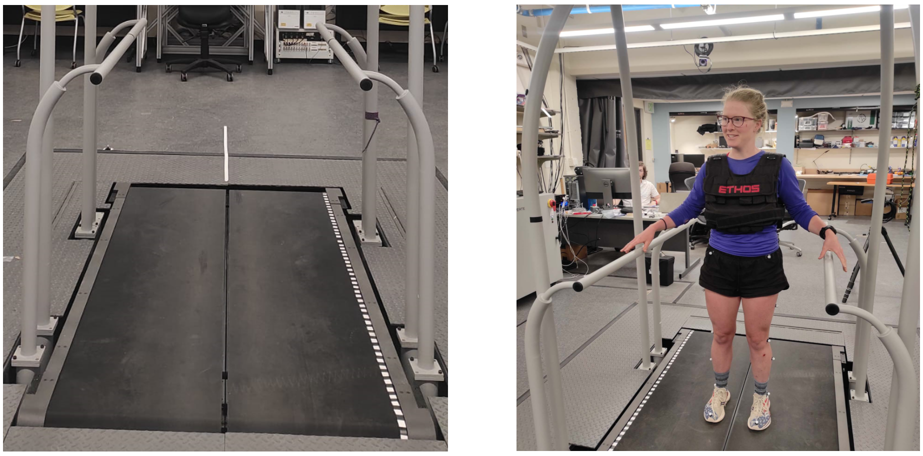
1. Introduction

Split-belt locomotor adaptation [1] is a rehabilitation technique for patients suffering from gait asymmetry following a neurological injury such as stroke. It aims at correcting the asymmetry by training the brain to learn a new walking pattern on a split-belt treadmill. A split-belt treadmill is a treadmill having two belts which can be controlled independently. During the exercise, one belt is usually made to run faster than the other. The leg of the patient is placed on the fast belt or on the slow belt depending on their initial asymmetry. The difference in belt speeds on a split-belt treadmill constitutes a perturbation that induces locomotor adaptation as the individual modifies or adjusts their walking pattern when performing the task. Most of the individuals who perform the task achieve to get closer and closer to gait symmetry towards the end of the task.



a) *b)*

Figure 1: a) Split-belt treadmill from the Neuromechanics Laboratory of the University of Colorado Boulder
b) Healthy individual ready for the split-belt treadmill exercise

Some studies have proven that split-belt locomotor adaptation could improve walking symmetry in post-stroke patients [2]. However, the main challenge remains to make this technique a long-term rehabilitation technique, aimed at transferring the learned movement for a longer period of time when the patient walks on level ground. Several optimization techniques have already been investigated [3]. This work focuses on investigating whether an increase in the effort incurred while performing the task affects how the individual learns the task and goes further to quantify the effort incurred by calculating joint moments through inverse dynamics.

For this purpose, ten healthy adult individuals were made to carry a load on their upper body while conducting a motion capture experiment during the split-belt walking task. Carrying a load while walking increases energy expenditure and therefore the effort incurred [4]. Two scenarios were investigated: a high effort condition (HE) - *carrying a load of 15% of their bodyweight* and a low effort condition (LE) - *carrying a load of 5% of their bodyweight.*

2. Description of the experiment and data collection

The ten healthy adults came in two separate visits: one for LE and the other for HE, in a randomized order. Sixteen reflective markers were placed on their lower body according to the Plug-in gait model [5], and each one carried a weight vest which constituted the load. The walking task lasted for about 42 minutes and consisted of walking on a split-belt treadmill pre-programmed to follow a specific sequence made of 7 blocks, each different in duration and belt speeds. The blocks were named *base1*, *base2*, *base3*, *split1*, *wash1*, *split2* and *wash2* blocks. This study primarily focuses on analysing data from the split1 block which consisted of walking for 10 minutes with split-belts (slow belt at 0.5m/s and fast belt at 1.5m/s). The data collected and recorded by the VICON Nexus motion capture software [6] consisted of marker positions at each time frame as captured by the optical cameras installed in the laboratory environment. Ground reaction forces were measured by the force plates beneath the BERTEC instrumented treadmill [7]. All the data obtained from the motion capture was saved in files to be used for consequent analysis. The most useful data was **marker positions** and **ground reaction forces.**

3. Data processing and Data analysis

Inverse dynamics was performed using the musculoskeletal software OpenSim [8] to obtain the joint moments. Joint moments describe the net sum of all internal moments delivered by all internal structures around the joint. The main joints investigated were the **hip**, **knee,** and **ankle joints.** Inverse dynamics computation requires joint angles from inverse kinematics and ground reaction forces from motion capture. Inverse kinematics obtains a pose of a subject's skeleton at each frame captured, based on the recorded marker positions relative to the global laboratory coordinate system. Inverse dynamics is then computed using the formula below :

Direction of computation ←

$$\boldsymbol{M} = \boldsymbol{I} * \propto$$

M *: joint moment*
I *: body segment inertia (provided by OpenSim)*
$\propto$ *: joint angular acceleration*

The ten minutes of split-belt walking consisted of about 700 strides. A stride is made up of two footsteps. Of these 700 strides only the last 30 were analysed in MATLAB. These refer to the strides during **late adaptation** which was more relevant to analyse since it's towards the end of the motion that individuals approach symmetry. Data collected from the slow leg (leg on the slow belt) was analysed separately from that collected from the fast leg (leg on the fast belt).

For each stride, the peak moment value was obtained both for the slow leg and the fast leg. These values were averaged across all strides to obtain a single peak value for each subject. Then, another average was done across all 10 subjects to obtain single bar plots for knee, hip and ankle joints, during HE and LE.

4. Results

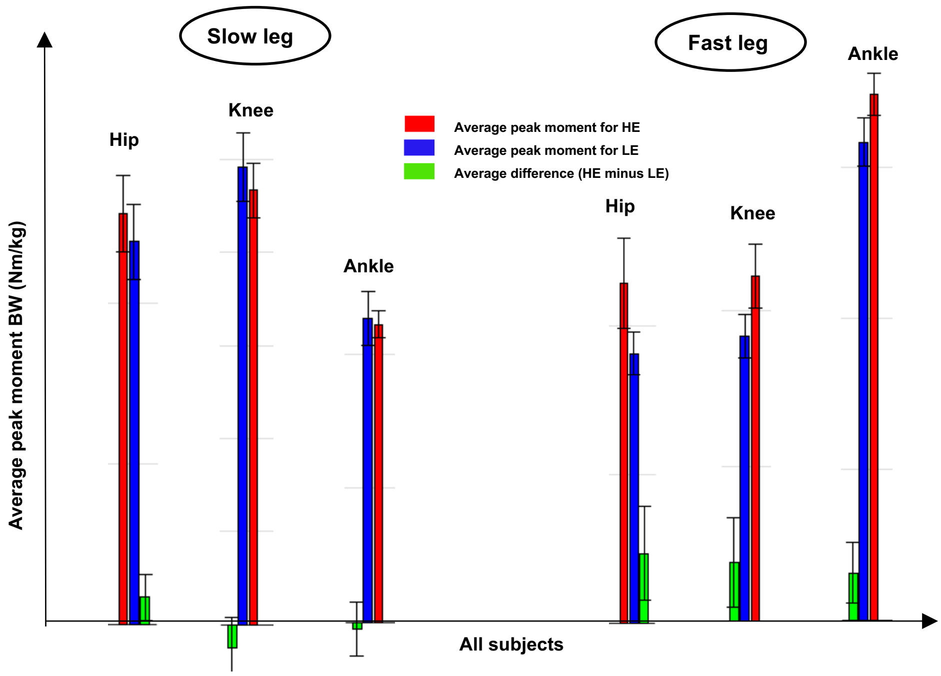


Figure 2: Barplots of average peak moments normalized to bodyweight at hip, knee and ankle joints across all 10 subjects for the slow leg and the fast leg

Table 1: Summary table

	Slow leg	Fast leg
Hip joint	**HE > LE**	**HE > LE**
Knee joint	**HE < LE**	**HE > LE**
Ankle joint	**HE < LE**	**HE > LE**

We first tried comparing HE to LE joint moments by plotting average peak moment values in the form of barplots. This gave us the results in the summary table below, and most importantly enabled us to identify potential outliers amongst the subject. From the individual barplots we obtained before making an average, we found out that subjects 5 and 9 were outliers because their barplots were in all cases out of range. We could not lay any conclusions from the results presented in the summary table above, that would have been statistically irrelevant. We therefore, went forward to conduct a paired t-test.

A paired t-test is a statistical test used to compare the means of two datasets when each observation in one dataset can be paired with an observation in the other dataset. This was the case with our data since each subject generated an average peak moment value in LE which could be paired to the value obtained in HE. A significance level α of 0.05 was used, to test the null hypothesis that the pairwise difference between the HE and LE data sets has a mean equal to zero.

p-value > 0.05 → accept the null hypothesis → HE < LE
p-value < 0.05 → reject the null hypothesis → HE > LE

Table 2 below contains the p-values obtained and the conclusions made without considering data from subjects 5 and subjects 9.

Table 2: Results summary for the comparison of HE and LE average peak moments (without subjects 5 and 9)

	Hip peak moment (hpm)		**Knee peak moment (kpm)**		**Ankle peak moment (apm)**	
	p-value < 0.05?	**conclusion**	**p-value < 0.05 ?**	**conclusion**	**p-value < 0.05?**	**conclusion**
Late adaptation **Fast leg**	**0.1189**	**HE < LE**	**0.0040**	**HE > LE**	**0.0316**	**HE > LE**
Late adaptation **Slow leg**	**0.1183**	**HE < LE**	**0.6407**	**HE < LE**	**0.0973**	**HE < LE**

When we exclude subjects 5 and 9, we observe that the knee and ankle peak moments are significantly greater in the HE condition than in the LE condition during late adaptation in the fast leg.

5. Discussion and Conclusion

Considering the results obtained from the paired t-test, it was found that, there is an increase in joint moments in the knee and ankle joints in the high effort condition in the fast leg during late adaptation. There is no increase in joint moments in the slow leg. Since the fast leg will be the most affected by the load carried during such an experiment, it will be important to consider the optimal speed of the fast belt to remain within an acceptable range of increase in joint moments. Further analysis should be made to relate this increase in joint moments to the learning of the split-belt treadmill walking task.

6. References

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