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

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Split-belt locomotor adaptation is a powerful tool used in gait rehabilitation to solve problems of asymmetric gait patterns. Making this tool more efficient by involving the decision variable "effort" is being investigated. Through inverse dynamics, it is possible to quantify the effort incurred when using this tool by computing joint moments.

Split-belt locomotor adaptation, split-belt treadmill, effort, inverse dynamics, joint moments.

L'adaptation à la locomotion sur tapis roulant à courroies séparées est un outil puissant utilisé en réadaptation de la locomotion pour résoudre les problèmes d'asymétries de marche. Rendre cet outil plus efficace en utilisant la variable décisionnelle qu'est "l'effort" est étudié. A travers la dynamique inverse, il est possible de quantifier l'effort déployé lors de l'usage de cet outil en calculant les moments articulaires.

L'adaptation à la locomotion, tapis roulant en deux parties, effort, dynamique inverse, moments articulaires.

1. Introduction

Following a neurological injury such as stroke, cerebral palsy, multiple sclerosis or Parkinson's disease, patients often suffer from gait disorders[1]. These impair their mobility leading to disability and a poor quality of life. However, gait disorders can be treated through gait rehabilitation[2]. The objective of gait rehabilitation is to strengthen the weakened body parts and foster motor learning. Some examples of gait rehabilitation techniques include: physical therapy involving gait training exercises, parallel bar training, robotic assisted gait training and treadmill training. A quite different approach to gait rehabilitation which makes use of the principle of locomotor adaptation and which is currently being thoroughly investigated, was the subject of this work. It is called the split-belt locomotor adaptation and it mainly aims at solving the problem of asymmetric gait patterns.

Locomotor adaptation is the process of modifying or adjusting an already well-learned movement in response to a perturbation in the environment through trial and error practice [1]. The split-belt locomotor adaptation technique uses a split-belt treadmill. It is a treadmill having two belts which can be controlled independently. One belt is often made to run faster than the other. The difference in speeds of the two belts constitutes the perturbation, obstructing the normal walking pattern, and training the brain to learn a new walking pattern. In a clinical setting, the paretic leg is either placed on the slow belt or on the fast belt depending on the patient's initial asymmetry (whether the paretic leg makes a shorter step or longer step). The aim of this technique is to reduce the initial asymmetry as the patient adapts during the task and the overall objective is to transfer the newly learned walking pattern to level ground walking for an improved quality of life.

Figure1 : Image from the Neuromechanics Laboratory of the University of Colorado Boulder showing a split-belt treadmill.

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[1]gait disorder : condition which affects your ability to walk
[2]gait rehabilitation : learning how to walk after sustaining an injury or disability

Split-belt locomotor adaptation has been proven to improve walking symmetry in post-stroke patients [2]. Its main drawback is that the learned movement is not often transferred to level ground walking or is transferred just for a short while (some few hours). Several studies have been made in order to improve this technique. The main improvement goals are finding how to learn the new walking pattern faster and how to transfer it to level ground walking for a longer period of time. From a Neuromechanics laboratory [3] perspective, which focuses on understanding how decision variables such as reward and effort influence movement control by the brain, it was fundamental to study the role of effort in split-belt locomotor adaptation.

Effort here is defined as the energetic cost of movement. It is the energy expended per unit distance travelled per unit bodyweight. It is a physical quantity measured in $Jkg^{-1}m^{-1}$. It can be measured indirectly using indirect calorimetry[3] or gait variables such as joint moments. Humans walk in a way that minimizes the effort they incur. Some studies have shown that as individuals regain gait symmetry during the split-belt treadmill task, they spend less energy, meaning that gait symmetry is associated with low energy expenditure [4]. Therefore, as research question, it was asked whether increasing the initial effort of performing the split-belt treadmill task by carrying a load for example, would affect how individuals learn the task. To answer this research question, an experimental study was carried out, during which healthy individuals performed the split-belt walking task while carrying a less heavy load (low effort condition) and repeat the task while carrying a heavier load (high effort condition). It was hypothesized that individuals would learn faster during the high effort condition than during the low effort condition in order to get rid of the high effort incurred faster.

The goal of this study was to quantify the effort induced by the load on the individuals performing the task. This was done by performing inverse dynamics in order to obtain the joint moments in the hip, knee and ankle joints of the individuals, and compare them between the low and high effort condition. Knowledge of the internal mechanisms occurring at the level of the joints during the task would be useful information for the development of more rational rehabilitation techniques.

To achieve this, the motion of each individual on the split-belt treadmill was tracked through motion capture using non-invasive passive reflective markers and optical cameras and recorded in the motion capture software *VICON Nexus* [5]. Inverse kinematics and inverse dynamics were performed using the *OpenSim software* [6] and finally, *MATLAB* [7] was used to process the results, analyse them and represent them graphically for easy interpretation.

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[3]indirect calorimetry : method to measure energy expenditure by calculating the amount of oxygen used VO_2 and the amount of VCO_2 released by the body

2. Description of the experimental study

Ten healthy adults (6 male and 4 female) aged from 18 to 35 years, were tested during the split-belt treadmill walking task in two effort conditions, one being carrying a load of 5% of bodyweight (low effort condition, LE) and the other being carrying a load of 15% of bodyweight (high effort condition, HE). They came in two separate visits, one for LE and the other one for HE in a randomised order. The experimental protocol was exactly the same on both visits, the only difference was the mass of the load carried. The load was steel blocks of 1.34kg (2.5 pounds) each, fitted in the pockets of a weight vest. The total mass of the load carried depended on the bodyweight of the individual as specified above, and was on average 3.3kg for LE and 11.8kg for HE. The motion was tracked and recorded using the VICON Nexus motion capture system consisting of 11 optical cameras recording at 1000Hz. The BERTEC [8] instrumented split-belt treadmill composed of force plates beneath each belt was the treadmill used for the experiment. Its force plates provided a measure of the ground reaction forces at 100Hz as the individual stepped on the treadmill. The whole setup was connected to the VICON Nexus software for data recording.

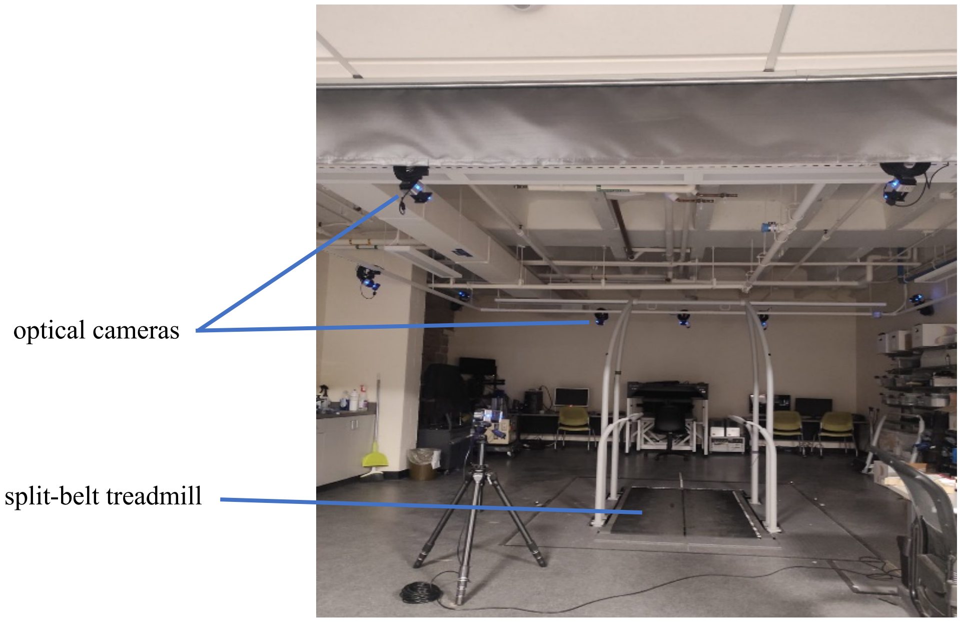

Figure 2 : Motion capture space to track the movement of the individual performing the split-belt walking task.

16 passive reflective markers were placed on the lower limbs of the subject according to the plug-in-gait model, with a little difference in that, the right thigh marker (RTHI) was higher than the left thigh marker (LTHI). This change was to enable an easier scaling in OpenSim and did not cause any problem for the data collection.

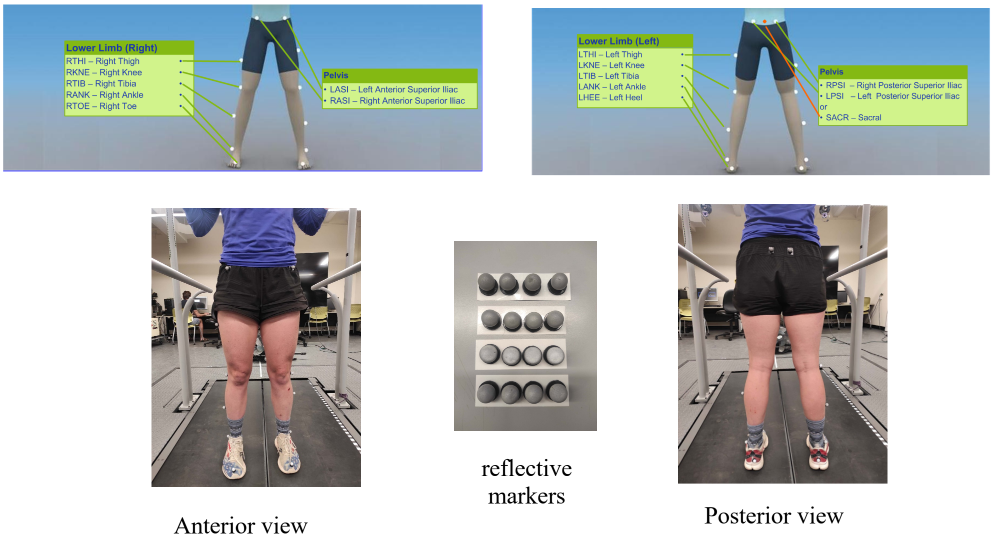

Figure 3 : Marker placement according to the plug-in-gait model, (16 markers in total).

A static trial was collected to generate the subject's skeleton according to marker placement.

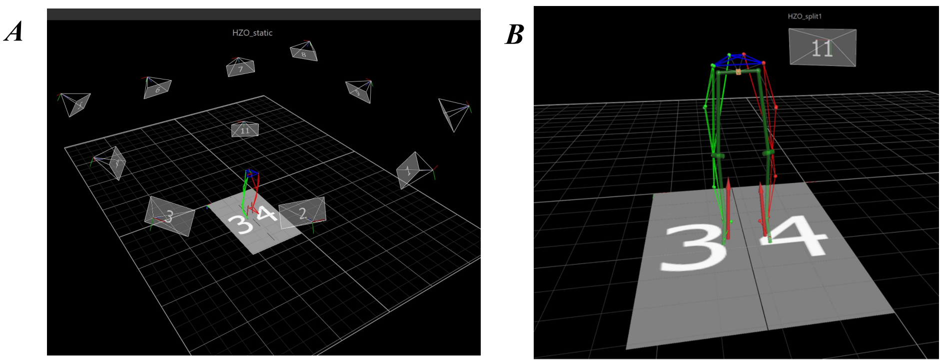

*Figure 1 : Capture space in the VICON-Nexus interface showing the tracking cameras (**A**) and the subject's skeleton during a static trial (**B**).*

The subject wore the weight vest and started the task following the experimental protocol presented in the section below.

Figure 2 : Images of the steel block, weight vest and a subject carrying the weight vest during the experiment (from left to right).

2.1. Experimental Protocol

The walking task had a total duration of approximately 42 minutes and consisted of walking on the split-belt treadmill pre-programmed to follow a specific sequence made of the 7 blocks presented below:

- **base1** : walking for 1 minute during which the treadmill belts were tied (moving at the same speed) at 0.5m/s.
- **base2** : walking for 2 minutes with tied belts at 1.5m/s.
- **base3** : walking for 2 minutes with tied belts at 0.5m/s.
- **split1** : walking for 10 minutes with split-belts (slow belt at 0.5m/s and fast belt at 1.5m/s).
- **wash1** : walking for 15 minutes with tied belts at 0.5m/s.
- **split2** : walking for 10 minutes with split-belts (slow belt at 0.5m/s and fast belt at 1.5m/s).
- **wash2** : walking for 2 minutes with tied belts at 0.5m/s.

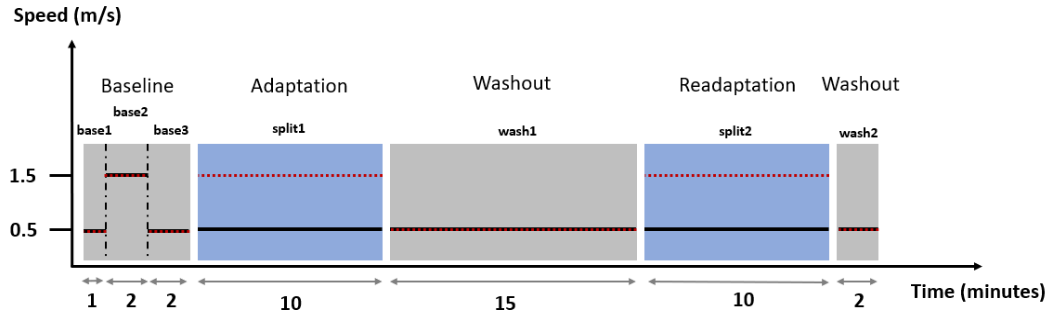

Figure 6 : Schematic representation of the split-belt treadmill experimental protocol

In this report, only the data from the split1 block will be analysed and discussed.

2.2. Data collection

Each force plate recorded the ground reaction forces**.** The camera system recorded the trajectories (marker positions at each frame) of each of the 16 markers. After data was recorded for each block, the trajectories were checked for any gaps in the data and gap filling was performed according to a best fitting algorithm in the software. Gaps occur when a marker is not visible by at least two cameras therefore making it impossible to estimate its position. Once all the gaps filled, the data was exported into specific file formats (***.csv, .trc*** and ***.mot***). The trc file contained the marker trajectories, and the mot and csv files contained the ground reaction forces.

3. Data processing

The musculoskeletal modelling software OpenSim was used to perform inverse kinematics and inverse dynamics. Inverse kinematics (IK) computes the joint angles from the marker position data and inverse dynamics (ID) uses these joint angles together with ground reaction forces (GRF) to compute joint moments.

To perform any modelling and computation in OpenSim, a model is needed. A model is an assembled body skeleton which may or may not possess a marker set. Several models are made available by OpenSim. For this work, the *full body musculoskeletal model-muscle actuated lower limb-torque actuated upper body* [9] developed by *Apoorva Rajagopal et al* was used. It came with a marker set which was adjusted in terms of number, position and naming, to match the marker set of the plug-in gait model Figure3.

A B

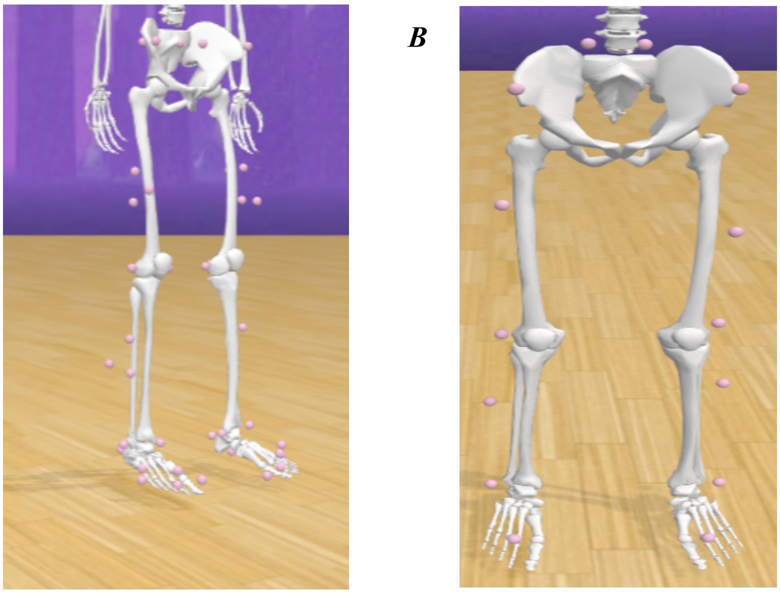

*Figure 7 : OpenSim model. Initial model(**A**) and adjusted model (**B**). Model markers represented by pink spheres.*

3.1. Scaling

The adjusted model was then scaled to match to each subject skeleton for each effort condition. The scaling was done using OpenSim's scale tool. This tool makes use of the file from the static trial during the motion capture experiment (*trc file*). This file specifies the marker positions on the subject during the capture time. The scale tool identifies the number of markers and the number of frames in the file. It scales the model based on scale factors obtained from the measurement of marker pair distance delimiting body segments, both in the model and in the experimental data and also scales based on the weight attributed to markers. For example, the RASI marker (right anterior superior iliac spine marker) and the LASI marker (left anterior superior iliac spine marker) are the marker pairs used for the measurement of the pelvis segment. The distance between RASI and LASI is measured in the model and in the experimental data. The overall scale factor is determined by dividing the greater measurement by the least. This scale factor tells by how much a body segment should be increased or reduced in size. The marker weight indicates how well we want the marker to be adjusted. We assigned higher weights to markers placed at joints. The scale tool proceeds by placing the markers on the model according to the marker position of the file from the static trial. The scale tool also takes into account the subject's body mass to estimate individual segment masses from which the inertia is determined. For this work, the model was scaled for both low and high effort conditions using the distinct files from their static trials. To take into account the mass added to the subject by the weight vest, we added that mass to the torso segment of the model after scaling, then saved the model. This was done for both low effort and high effort conditions. To assess the scaling results, it was always ensured that the total squared error was less than 1 cm and that the maximum marker error was less than 2cm. This was done by adjusting the weights attributed to the markers. Once the model was scaled to each subject, for each effort condition, inverse kinematics could then be performed.

3.2. Inverse kinematics

The OpenSim IK tool uses the trc file of the motion block to be processed. It steps through each time frame of experimental data and positions the model in a pose the "best matches" experimental marker and coordinate data for that time step. This "best match" is the pose that minimizes a sum of weighted squared errors of markers. By matching model markers to experimental data at each time frame, the joint angles vary and are measured by the tool with respect to its own reference coordinates. The output of the IK tool is a motion file (***.mot***) and a storage file (***.sto***) that contains the joint angles computed by IK.

3.3. Inverse dynamics

OpenSim uses the IK results and the GRF from the *mot file* from Nexus, to compute generalized forces; that are the net forces and torques (moments) at each joint responsible for a given movement. The resulting file is an *sto file*. Inverse dynamics computation is made from the inertia of the body segments, *I*, provided by OpenSim, the joint angular acceleration, ∝, computed from the joint angles and the ground reaction force data regarded as external loads. The formula to obtain the joint moments, *M*, is shown below:

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

← Direction of computation

To summarise, the results obtained from OpenSim are the joint angles stored in an *sto file* and the joint moments stored in an *sto file* as well.

4. Data analysis

The data was analysed in Matlab according to typical characteristics of the gait cycle. In order to better understand the data analysis section, a brief description of the gait cycle will be made.

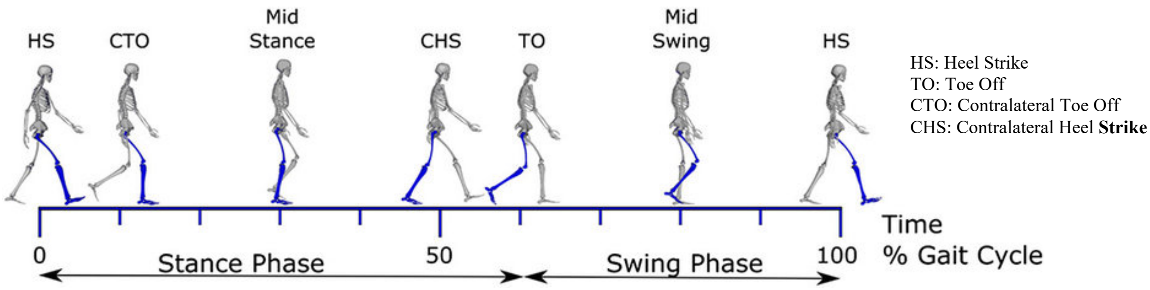

Figure 8 : Schematic representation of the gait cycle.

A walking gait cycle starts with foot contact with the ground of one leg and ends with the next foot contact with the ground of the same leg as shown in Figure8 above (leg highlighted in blue). The initial foot contact by the leading foot (foot initiating the gait cycle) is known as the ***heel strike*** (HS). The gait cycle is therefore the interval between the heel strike of one leg and the next heel strike of the same leg. The gait cycle constitutes a ***stride*** and has a length called the ***stride length***. A stride is made up of two ***steps***. A step is the interval between the heel strike of the leading foot and the heel strike of the other foot. Humans walk by making left and right steps.

The split1 block consisting of 10 minutes of split walking has about 700 strides. The first strides are made up of very asymmetric steps due to the belt speed difference, but the last strides are made up of more symmetric steps since the individual gradually adjusts their walking pattern to achieve gait symmetry. The whole block is analysed as a percentage of the gait cycle by identifying HS to HS values. Heel strikes are identified from ground reaction force data by using a threshold force value. Once the threshold is exceeded in the force data, a heel strike force is recorded. These datapoints are then used to navigate joint moment data and extract data at each successive heel strike. Each group of extracted values differ in length, so they are interpolated using 100 query points to make them of the same length, and finally we find the average over all the data points to have only a single data set representative of a percentage of a the gait cycle.

For split-belt walking, the data collected from the fast leg and the data collected from the slow leg was analysed separately, and was further divided into early adaptation (average over the first 5 strides of motion) and late adaptation (average over the last 30 strides of motion). This was done because, since split-belt walking is a learning process, it would be interesting to analyse its beginning and end in order to identify any differences. The results will present late adaptation only, since it is the most important part to investigate given that it is at the end of the split-belt walking task that individuals adapt and get closer and closer to gait symmetry.

Data was represented in Matlab by plotting graphs of joint moments versus percent gait cycle, a peak analysis was made to determine the peak moments per stride and finally, a statistical analysis was performed using a paired-t test to compare peak moments in LE and HE.

5. Results

The results will be presented by plots of joint moment profiles during the split1 block. Bar plots will also be plotted to compare the peak values of the joint moment curves between both effort conditions. Finally, a paired t-test will be performed for a quantitative comparison of the joint moments in HE and LE conditions. Throughout this result presentation, the **coral color** will be used to represent the HE condition, the **teal color** for LE condition, the fast leg will be differentiated from the slow leg by using darker colors for the slow leg; **dark coral** for HE and **dark teal** for LE.

Summary

HE: **coral color**	fast leg HE: **coral color**	slow leg HE: **dark coral**
LE: **teal color**	fast leg LE: **teal color**	slow leg LE: **dark teal**

5.1. Dynamics profiles between HE and LE for slow leg and fast leg

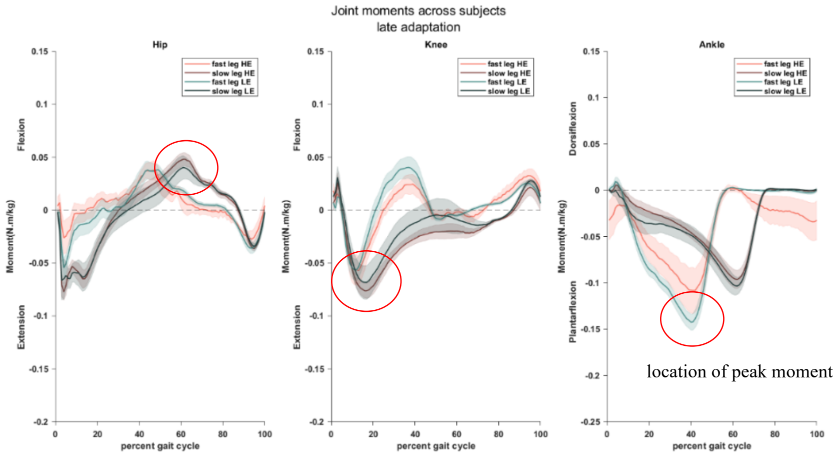

Figure 9 : Dynamics of hip, knee and ankle joints of slow leg and fast leg during late adaptation in HE and LE.

The above three plots are plots of the average hip moment, knee moment and ankle moment averaged across the 10 subjects as a function of a percentage of the gait cycle. The joint moments have been normalised to bodyweight (*Nm/kg*). On each plot, four curves are drawn. Each curve illustrates the joint moment profile for either the slow leg or fast leg during either the HE or LE condition (their colours distinguish them). The profiles obtained are consistent with what is expected from literature. The curves will be compared at their peak values as highlighted by the red circles in Figure9 above.

Observations

The hip and knee peak moments for the slow leg are greater during HE than LE, contrary to the ankle peak moment which is lower during HE. For the fast leg, the hip and knee peak moments show little noticeable difference contrary to the ankle peak moment which is lower in HE as observed for the slow leg. We notice that the slow leg and fast leg show differences in their comparison between HE and LE.

However, an accurate comparison between HE and LE joint moments can not be done, just by observing these curves. This is why a peak analysis was performed in which the peak moment in each profile was identified, for each stride and for each subject then, averaged across all strides to obtain a single value.

This will be represented by plotting bar plots of average peak moments against subject number, for the slow and fast legs during late adaptation.

5.2. Bar plots comparing average peak moments between HE and LE

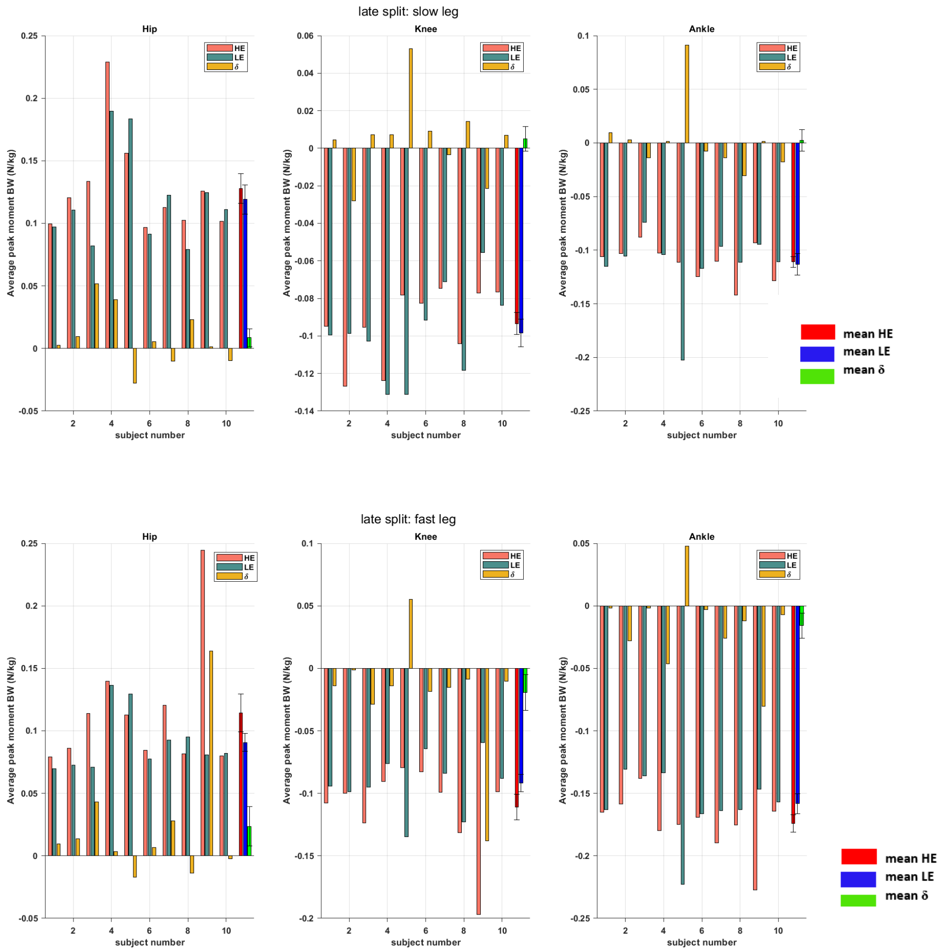

*Figure 10 : Bar plots of average peak moment normalized to BW for all 10 subjects in HE (coral bar) and LE (teal bar), difference delta (HE minus LE, yellow bar), average peak moment across the 10 subjects (red bar average HE, blue bar average LE) and average difference (green bar) for slow leg (**A**) and fast leg (**B**).*

The bar plots above show bar triplets for each of the ten subjects (in colours coral – teal - yellow). The last bar triplet (in colour red – blue – green) shows the mean across the 10 subjects. The coral bar indicates the HE average peak moment. It is a single number which is the average of all the peak moments per stride during the motion in the HE condition. The teal bar indicates the LE peak moment. It is also a single number which is the average of all the peak moments per stride during the motion in the LE condition. The yellow bar is the difference between these two values. For the hip peak moment:

- a positive yellow bar indicates HE peak moment is greater than LE peak moment
- a negative yellow bar indicates HE peak moment is less than LE peak moment

For the knee and ankle, since their peak moments are negative:

- a positive yellow bar indicates the LE peak moment is greater than the HE peak moment
- a negative yellow bar indicates the LE peak moment is less than the HE peak moment.

To make a conclusion about which effort condition has a higher peak moment, we first referred to the last bar triplet which is the average across subjects and in particular the last bar (green bar) and its standard error bar. If we denote the mean as μ and the standard error as SE , the standard error bar indicates $\mu \pm 1SE$ on either sides of the mean value. In order to stay in the 95% confidence interval that HE > LE, $2 * SE$ should remain greater than zero. So, if we double the length of the error bar, we want to make sure that it remains above 0 to conclude that the HE > LE.

Observations

Subjects 5 and 9 seem to be outliers because of their peak moments which are always out of range compared to other subjects. We therefore decided to discard subjects 5 and 9 in the second round of paired t-test since those would greatly influence the results and make them not significant.

5.3. 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.

- If the p-value obtained > 0.05, we accept the null hypothesis, which implies there is no significant difference between HE and LE or again that the HE condition is not significantly greater than the LE condition.

- If the p-value < 0.05, we reject the null hypothesis, and therefore there is a significant difference between HE and LE.

Table 2 below contains the p-values obtained and the conclusions made.

Table of comparison of peak moments between LE and HE conditions (with subjects 5 and 9)

HE and LE significantly different (green) — HE and LE not significantly different (red)

	Hip peak moment (hpm)			**Knee peak moment (kpm)**			**Ankle peak moment (apm)**		
	observations from barplot	**p-value < 0.05?**	**conclusion**	**observations from barplot**	**p-value < 0.05 ?**	**conclusion**	**observations from barplot**	**p-value < 0.05?**	**conclusion**
Fast baseline	HE > LE	0.0216	hpm significantly greater in HE	HE < LE	0.4563	kpm not significantly greater in HE	HE < LE	0.5598	apm not significantly greater in HE
Slow baseline	HE < LE	0.6508	hpm not significantly greater in HE	HE < LE	0.4264	kpm not significantly greater in HE	HE < LE	0.9155	apm not significantly greater in HE
Early adaptation Fast leg	HE < LE	0.3339	hpm not significantly greater in HE	HE < LE	0.3532	kpm not significantly greater in HE	HE < LE	0.3510	apm not significantly greater in HE
Late adaptation Fast leg	HE < LE	0.1890	hpm not significantly greater in HE	HE < LE	0.2307	kpm not significantly greater in HE	HE < LE	0.1669	apm not significantly greater in HE
Early adaptation Slow leg	HE < LE	0.8309	hpm not significantly greater in HE	HE < LE	0.2709	kpm not significantly greater in HE	HE < LE	0.6912	apm not significantly greater in HE
Late adaptation Slow leg	HE < LE	0.2832	hpm not significantly greater in HE	HE < LE	0.4923	kpm not significantly greater in HE	HE < LE	0.8375	apm not significantly greater in HE

Table 1 : Results summary for the comparison of HE and LE average peak moments (with subjects 5 and 9)

From the p-values of the paired t-test above, we can conclude that there is no significant difference between the HE and LE peak joint moments during the split-belt adaptation task. This conclusion is made taking into account all the 10 subjects, but since we noticed subjects 5 and 9 might be outliers, another paired t-test was made, this time discarding these subjects. The results are shown in Table2 below.

Table of comparison of peak moments between LE and HE conditions(without subjects 5 and 9)

HE and LE significantly different (green) HE and LE not significantly different (red)

	Hip peak moment (hpm)			Knee peak moment (kpm)			Ankle peak moment (apm)		
	observations from barplot	**p-value < 0.05?**	**conclusion**	**observations from barplot**	**p-value < 0.05 ?**	**conclusion**	**observations from barplot**	**p-value < 0.05?**	**conclusion**
Fast baseline	HE > LE	0.0199	hpm significantly greater in HE	HE < LE	0.8379	kpm not significantly greater in HE	HE > LE	0.0143	apm significantly greater in HE
Slow baseline	HE < LE	0.1817	hpm not significantly greater in HE	HE < LE	0.9247	kpm not significantly greater in HE	HE < LE	0.0662	apm not significantly greater in HE
Early adaptation Fast leg	HE < LE	0.1795	hpm not significantly greater in HE	HE < LE	0.8336	kpm not significantly greater in HE	HE < LE	0.4383	apm not significantly greater in HE
Late adaptation Fast leg	HE < LE	0.1189	hpm not significantly greater in HE	HE > LE	0.0040	kpm significantly greater in HE	HE > LE	0.0316	apm significantly greater in HE
Early adaptation Slow leg	HE < LE	0.6959	hpm not significantly greater in HE	HE < LE	0.4584	kpm not significantly greater in HE	HE < LE	0.9437	apm not significantly greater in HE
Late adaptation Slow leg	HE < LE	0.1183	hpm not significantly greater in HE	HE < LE	0.6407	kpm not significantly greater in HE	HE < LE	0.0973	apm not significantly greater in HE

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

When we exclude subjects 5 and 9, we can make another conclusion. 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.

6. Discussion

The goal of this study was to determine joint moments during the split-belt treadmill walking task in high and low effort conditions and compare them between these two effort conditions. It was found that, most of the changes in joint moments occur during late adaptation in the fast leg. The knee and ankle peak moments are significantly greater in HE condition than in LE condition in the fast leg during late adaptation. This was observed when considering a population of 8 subjects instead of 10 subjects. 2 subjects were discarded due to their incorrect dynamics profiles.

In order to relate these findings to learning of the task, further analysis could be done in order to identify from which stride a significant increase in peak knee and ankle moment in HE is noticeable, then observe the trend from this stride to the end of the motion in the learning curves of step length asymmetry.

7. Conclusion

The findings of this study reveal that increasing effort by carrying a load during the split-belt treadmill walking task increases knee and ankle peak moments in the fast leg during late adaptation. Further analysis should be made in order to relate this increase in joint moments to the learning of the split-belt treadmill task.

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