EXPLICIT CONTROL OF STEP TIMING DURING SPLIT-BELT WALKING

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Humans have the great ability to adapt their walking to different situations imposing distinct motor demands. However, people suffering from neurological disorders often adopt asymmetric walking pattern, affecting their mobility. It has been proposed that people can adapt spatial and temporal gait features independently when exposed to new environmental conditions. For example, previous work indicates that subjects can adapt *when* they step (i.e., step timing) without changing *where* they step (i.e., step position). New environments can be recreated using a split-belt treadmill that moves their legs at different speeds. Interestingly, this independent adaptation of spatial and temporal gait features has only been observed when subjects voluntarily modify the adaptation of spatial walking features (e.g., step position).

This raises the question of whether temporal gait features (e.g., step timing) can be also altered voluntarily without affecting the adaptation of spatial ones. To address this question, we contrasted the adaptation of spatial and temporal gait features when subjects walked on a split-belt treadmill under two conditions: 1) temporal feedback condition and 2) control condition. The temporal feedback group received visual feedback indicating when to step to prevent the adaptation of step timing during split-belt walking, while the control group walked without receiving any visual feedback. Kinematic and kinetic data was recorded during the entire duration of the experiment.

We found that subjects in the temporal feedback group could modulate their step timing in order to maintain a stepping rhythm similar to tied walking. In addition to this, modifying subjects' step times reduces the impact of the perturbation, and therefore reduces the spatial adaptation.

Independently of the feedback, all subjects experienced the same belt speeds on the treadmill. We show that despite being exposed to the same conditions, subjects are actually able to adapt in a way that they feel less perturbed.

This study shows promising result on the possibility of establishing a relationship between spatial and temporal gait features, and therefore being able to help develop rehabilitation processes. For patients who show asymmetries in only one domain, this could be particularly useful since it could allow to target specific motor outputs.

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1.0 INTRODUCTION

Humans can easily navigate distinct terrains without falling and it has been proposed that this is achieved by adapting spatial and temporal gait features. In the laboratory, this has been studied using a split-belt treadmill, which has two belts that can be moved at different speeds. This device allows us to create novel environmental conditions. It has been shown that people can adapt their gait and store new walking patterns when step asymmetry is perturbed (Reisman et al. 2005). It has been proved that spatial and temporal gait features contribute to recovering step length asymmetry when perturbed (Finley et al. 2015). It has also been suggested that this is achieved by independently controlling step position step time (Malone and al. 2012). However, this independence has only been shown by modulating the spatial features of gait. It is yet unknown if the adaptation of step time can be altered without affecting the adaptation of spatial features.

We are interested to whether humans can control explicitly temporal gait features. Central Pattern Generators (CPG) are neural networks that regulate temporal gait features, and they can be found encoded in low levels of the spinal cord (Marigold and al, 2015). Conscious corrections of gait have been observed in the spatial domain (Malone and Bastian, 2010). However, it is unknown if the stepping time, which are regulated by deep levels of the neural system, can be voluntarily altered.

Step length asymmetry is often considered to be a parameter highly influenced by the spatial control of limb, while temporal control often isn't. Stroke patients present spatial and/or temporal asymmetries (Malone and Bastian, 2014), but it has been shown that most of the reported asymmetries are found in the temporal domain (Peterson and al, 2010). It has been proved that step length asymmetry could be recovered by targeting only one gait parameter, i.e. spatial or temporal features (Finley, 2015). Patients with hemiparesis are asymmetric in spatial and temporal aspects of gait. Thus, we want to know if it is possible to specifically target one of them, and how.

To summarize the questions addressed in this study, we want to first know if humans are able to control their step timing voluntarily, and if so, we are interested in knowing if the adaptation of step position is independent from that of step time. We will also see if it is possible to prevent the adaptation of step time in a split-belt environment. If so, we will find out if the adaptation of step position alone can fully recover step length asymmetry.

2.0 METHODS AND EXPERIMENTAL PROTOCOL

2.1 EXPERIMENTAL PARADIGM

2.1.1 Subjects

Fourteen young healthy subjects participated in this study, forming two groups of seven subjects. The first group called “control group” was exposed to the speed profiles with no instructions or target, allowing subjects to adapt completely on their own. The second group, called “temporal hold” group, was given a visual feedback during certain trials, with special targets to reach. Table 1 summarizes the demographics who participated in the study,

Table 1: Description of the participating population

SUBJECTS	TEMPORAL HOLD GROUP	CONTROL GROUP
NUMBER N	7	7
AGE	23 (+/- 3)	24 (+/- 3)
MALE/FEMALE	4/3	3/4

2.1.2 Protocol

Each group was asked to perform the same four trials: *baseline*, *familiarization*, *adaptation* and *post-adaptation*. The first two trials were tied belt trials, with a set baseline speed of 0.75 m/s for 150 strides (about 3 minutes). Adaptation was a split belt trial, where the speed for the dominant leg was 1 m/s and the non-dominant leg 0.5m/s, for 600 strides (about 13 minutes). Dominant leg is commonly determined by which foot they would place forward first when tripping, or which foot they would use to kick a ball. For the last trial, post-adaptation, belts were tied again and set at a speed of 0.75 m/s for 450 strides (about 10 minutes). The control group performed all four trials with no feedback or instruction, therefore they represent “natural” adaptation to the paradigm. The temporal hold group was given a visual temporal biofeedback during familiarization and adaptation. We ran a familiarization trial for subjects in the temporal feedback group to get habituated to using the feedback to control their step time. Both groups went through familiarization trial since we wanted subjects from both group to go through the same extent of walking. The speed profiles are illustrated in Figure 1.

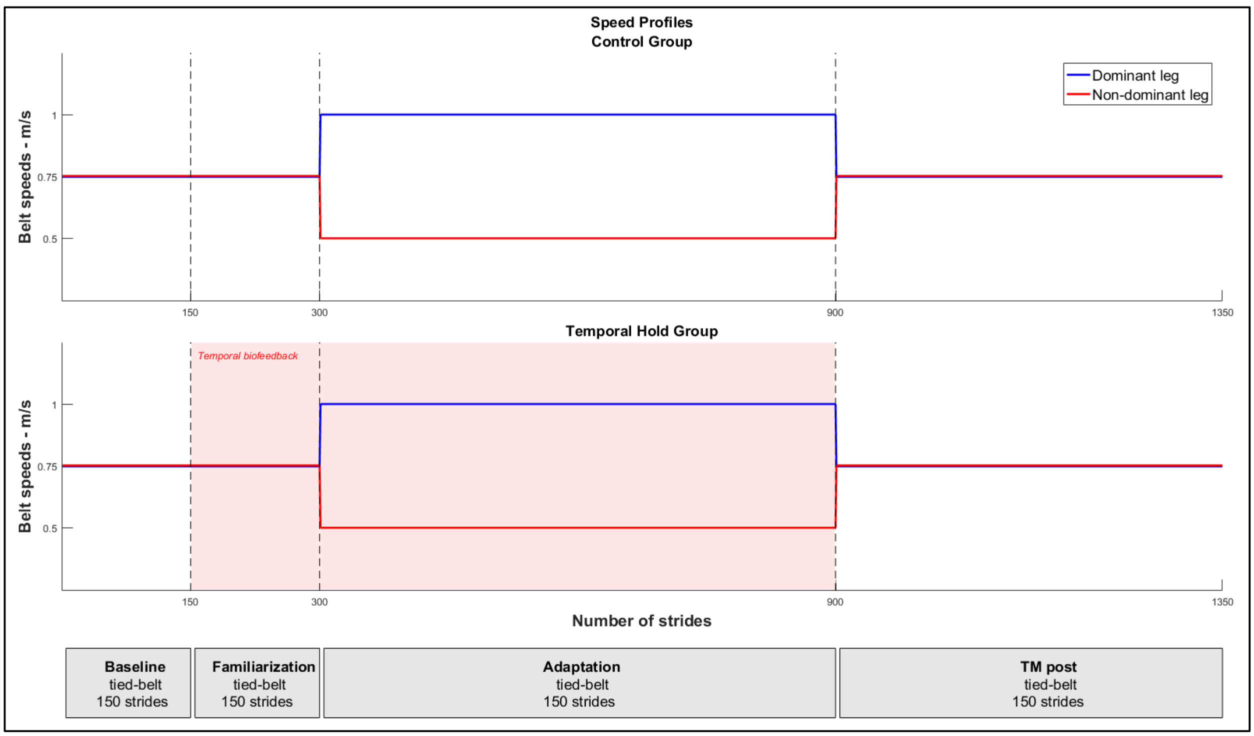

Figure 1: Speed profiles for both control and temporal hold groups. The blue line represents the dominant leg (which is always the fast leg while the red line is the non-dominant leg. The pink rectangle indicates when the subjects were given visual feedback

2.1.3 Visual Temporal Biofeedback

It has been shown that subjects reach an asymmetric step timing when walking in split belt condition (Finley JM, Long AW, Bastian AJ and Torres-Oviedo G, 2015). In this study, we aimed to use a visual feedback to reduce this asymmetry to baseline behavior, as illustrated in Figure 2.

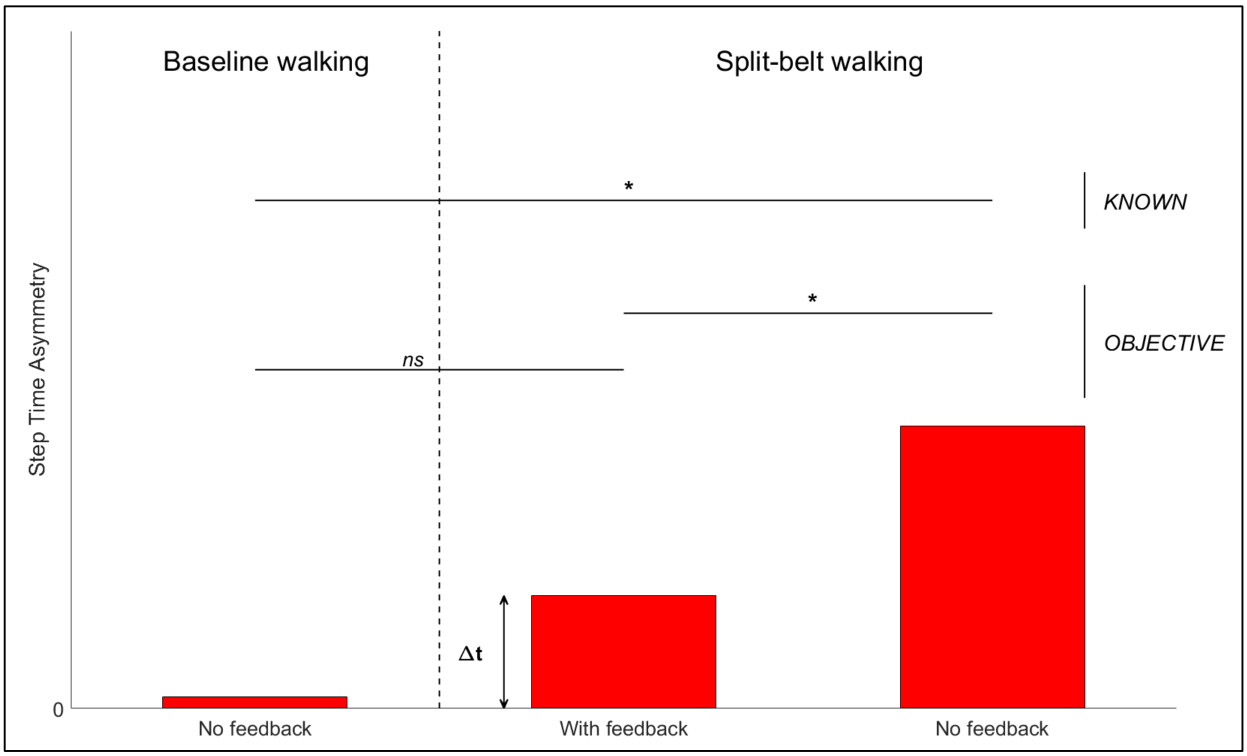

Figure 2: Graphic representation of the temporal feedback's objectives. The pink rectangle indicates a condition receiving feedback. "*" indicated significant difference, "ns" a non-significant difference.

As represented in Figure 2, we can know subject's step time asymmetries when they don't receive any feedback. The baseline behavior – tied belt condition – is be very close to zero, since this is a natural, symmetrical way of walking. In the split-belt condition, subjects will have large step time asymmetries, due to difference in belt speeds ("known" bar). The objective of the feedback is to force subjects to reach a step time asymmetry in the split belt walking with feedback

(Δt) that is not different from the one of baseline. Accordingly, it will also be significantly different from the split belt condition without feedback. ("objective" bars).

The feedback, displayed on a monitor in from of the treadmill, shows two step time targets that the subjects are asked to reach, as well as real time feedback on their current step time. Since we try to prevent them from having any temporal asymmetries the targets are the same, putting the boxes at the same height. At the end of each step they get a yellow bar to indicate the step time they took, and if they reached target (i.e. the yellow bar hits the box), then the box turns green.

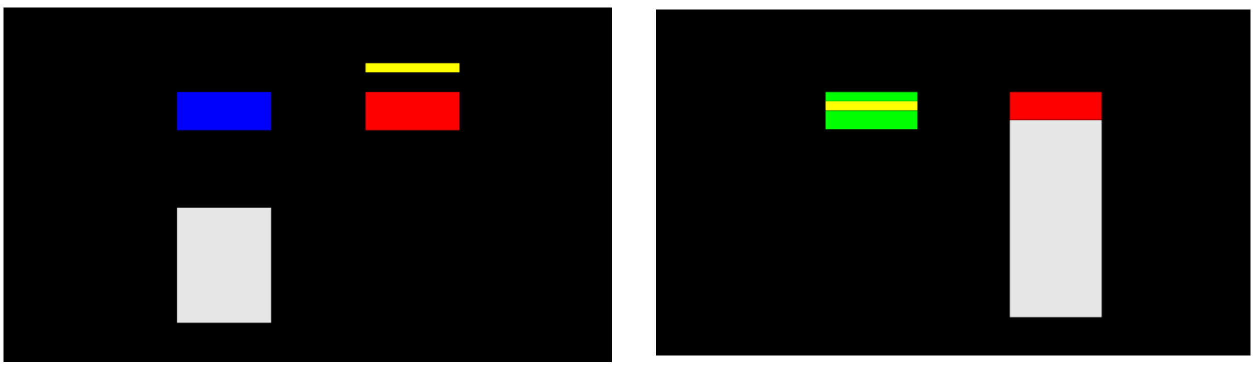

Figure 3: Screenshots of the visual temporal feedback. The red and blue boxes are the step time targets that the subject is trying to hit. Grey bar is real time feedback of the current step time; yellow bar is the step time from the contralateral leg. On the left image, the subject overshot the right leg's target, reaching a step time slightly longer than asked, and he is currently standing on his left foot (the grey bar would be going up). On the right image, the subject has reached target for the left leg and will reach it with the right leg if he switches to the next step at this instant.

The temporal biofeedback was coded in Python, using Wizard Software. Python was chosen over MATLAB for speed purposes, since we needed a real time "stride-by-stride" feedback. The control computer is connected to an external monitor placed in front of the subject during the trials. Two boxes appeared on the screen at a same height, representing the step time target, and moving bars represent the step time – step from ipsilateral Heel Strike (HS) to contralateral HS. The subject gets a real life feedback of the time spend on each leg, by seeing this bar going up towards the target box, as well as a "final" feedback for each step, indicated by a small yellow bar i.e. your total step time for each leg. If the target is reached the box turns green to indicate that the task has been rightfully executed. The boxes have a height equivalent to 0.05 s, which is the tolerance we arbitrarily decided for the target. Screenshots of the feedback can be seen in Figure 3.

The temporal biofeedback target was calculated from measured parameters in the first trial; at the end of *baseline*, we run a quick MATLAB program that computes the mean step times for each leg. Those two values are typically very close, since healthy subjects walk symmetrically. The target given was then the mean those two means. Note that both legs are given the same target, since we are trying to prevent subjects from adapting temporally, i.e. forcing them to have equal step times.

$$Target = \frac{1}{2}(mean\ step\ time_{right} + mean\ step\ time_{left})$$

2.2 DATA COLLECTION

2.2.1 Markers and anatomical landmarks

Since our study was solely focused on gait, only lower limb movement was recorded. All subjects were asked to wear skin-fitted shorts or pants, reducing the movement of the clothes with respect to the skin as much as possible, and comfortable sports shoes. Then, markers were carefully placed on their lower limbs, on specific bony landmarks. The markers are circular reflective surfaces, picked up by the infrared cameras in the lab. Before collecting data, we make sure that these markers are the only reflective elements picked up by the cameras. Shiny sneakers or clothing elements worn by subjects had to be covered in black duct tape. Table 2 summarizes the markers of interest for this study, the marker name is the anatomical landmark abbreviation used in the data collection software.. Previous gait studies have established parameters that we will compute from those four markers.

Table 2: Makers list and anatomical landmarks.

MAKER #	MARKER NAME	ANATOMICAL LANDMARKS
5	RGT	Right Greater Trochanter
9	RANK	Right Ankle
10	LGT	Left Greater Trochanter
16	LANK	Left Ankle

2.2.2 Experimental set-up

The testing room is equipped with a split belt custom built treadmill (BERTEC Corporation, OH), mounted on four force plates (sampling rate 1000 Hz). In front of the treadmill, a custom built safety handrail is also mounted on force plates, recording forces to monitor holding or touching during the trials. Around the room, 14 infrared cameras (VICON, sampling rate 100 Hz) are soundly installed to record any motion on or around the treadmill. Figure 4 is a picture of the experimental setup and Table 3 describes the main components of the testing equipment.

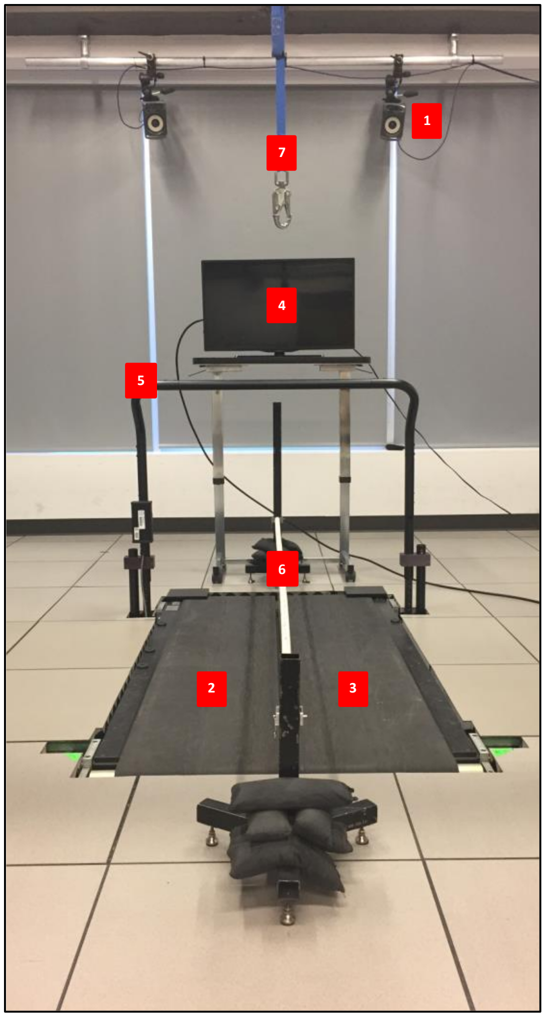

Figure 4: Picture of the experimental set up

Table 3: Experimental setup main components

#	DESCRIPTION
1	One of the 14 infrared VICON cameras
2	BERTEC treadmill – Left belt
3	BERTEC treadmill – Right belt
4	Monitor for visual biofeedback
5	Safety handrail
6	Safety belt separator
7	Safety harness hook

During calibration we make sure that the system is aware of all reflective surfaces in the room, so that it can ignore them all, and only pick up the reflection on the 18 markers positioned on the subject. The cameras are controlled by NEXUS, a data collection support software distributed by VICON. The treadmill belts are controlled though a MATLAB custom built Graphic User Interface (GUI), which acts a remote for the BERTEC software. In NEXUS, a trigger is also defined so that the activation of the MATLAB GUI automatically sets the cameras to start recording.

After a subject specific calibration of the system, and according labeling, NEXUS builds a functional skeleton of the subject, recording all the kinematic data for each marker. Identically, after calibration of the force plates, all ground reaction forces are recorded.

Subjects were asked to wear a safety harness during the experiment, and the treadmill has a safety handrail in front of the belts. Since walking patterns can be altered while holding to a handrail, subjects were asked to touch the handrail only if they felt like they were going to fall. The handrail is mounted on force plates and reaction forces were recorded throughout the experiment.

Another safety feature is the presence of a Plexiglas separator between the two belts, in order to make sure that subject could not step on the wrong belt. This was necessary since all subjects were asked not to look at their feet during the whole experiment, and to look straight ahead.

2.3 DATA PROCESSING

2.3.1 Stride cycle decomposition

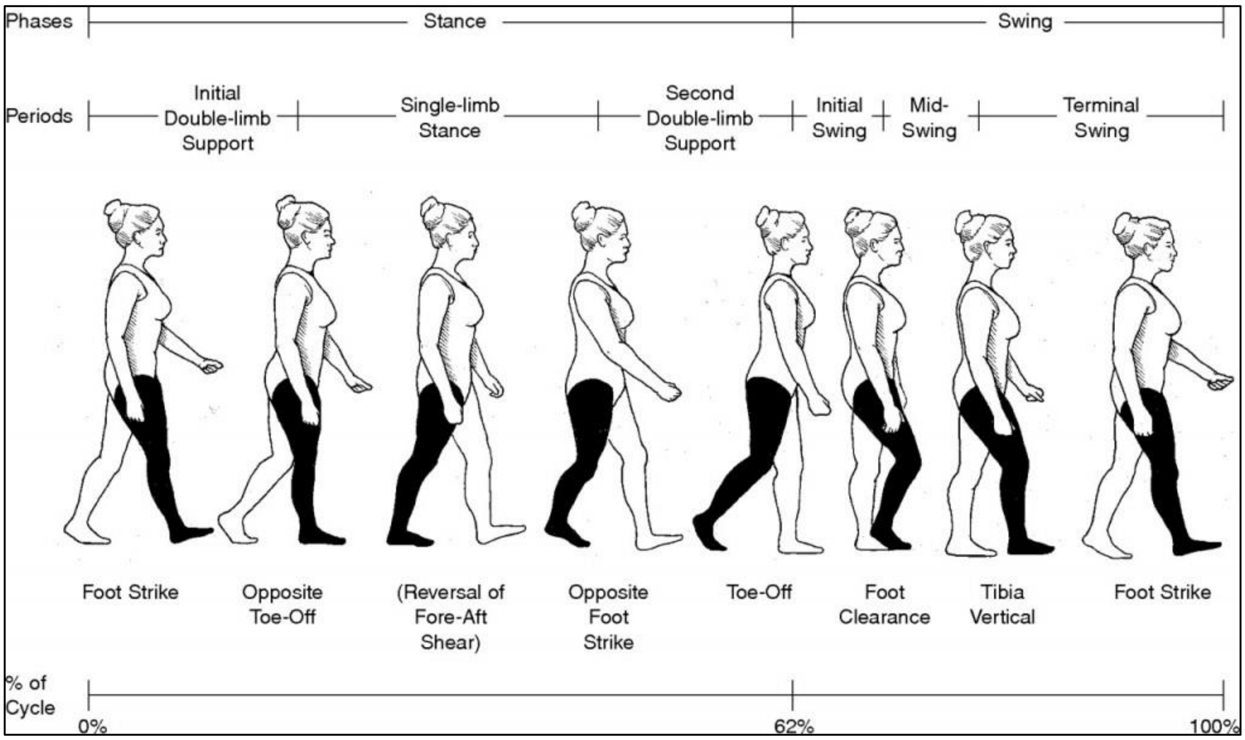

Figure 5: Gait cycle decomposition. On full stride is represented here, from heel strike to the next heel strike. All the different stride phases, as well as the % of cycle at which they occur are also represented. (Source: Journal of AAOS)

As illustrated in Figure 5, walking is a periodic activity, each period being called a stride cycle. A stride is the sum of two steps, which are defined by ipsilateral HS to contralateral HS. Therefore, a stride cycle is simply defined as HS to the next HS of the same leg. Strides cycles have two “states”: double support, when the two feet are touching the ground, and single support when only feet is on the ground. Looking at individual legs, the phase during which the foot is touching the ground is called stance, while the phase where the foot is in the air is called swing.

2.3.2 Event detection

We used both kinetic and kinematic data for event detection in this study. Kinetic data was processed since it is a more accurate technique for event detection (heel strike and toe off); it is also consistently used in walking studies. Kinematic data has been most commonly used in split-belt studies as well as to describe step length asymmetries. Therefore, to be able to compare our results with the ones from the literature, we processed both sets of data in this study.

Kinematic data was interpolated when markers of interest were occulted using built-in NEXUS tools. Once the gaps are filled, we look for any other reflective surface or parasite that could have been picked up during the data collection, and delete them. We now have clean files of the markers complete kinematics, as well as all the recorded ground reaction forces. Using a custom built MATLAB program we transform those files into MATLAB files, defining a long list of gait parameters, calculated from the events detected. Four types of events are defined in one stride cycle: SHS (heel strike of the slow leg), FHS (heel strike of the fast leg), STO (toe off of the slow leg) and FTO (toe off of the fast leg). However, since we have two set of data, kinetics and kinematics, we have two ways to calculate these events detection.

In order to understand the difference between computing parameters using kinetics or kinematics for event detection, it is useful to understand the details of a stride cycle and identify its phases. Figure 6 illustrates how the step times are computed for each set of data, showing the transverse amplitude of the ankle marker with respect to the hip position. Of course, this is a simplified model for graphic representation; the actual angle data may have different periods and amplitudes, as well as an evolution through time. We can see an offset in time between the events, the kinetic events (HS) occurring slightly later than the kinematic event. This delay is simply due to biomechanical constrains, in the sense that your feet do not land on the ground when your lower limb angle is at its maximum. After reaching maximum angle, the foot “retracts” towards the body, allowing the knee to bend, and this is when heel strike happens. This time will be called *retraction time.* A simplified representation of how events are computed, using both sets of data, as well as the retraction times, can be found in Figure 6.

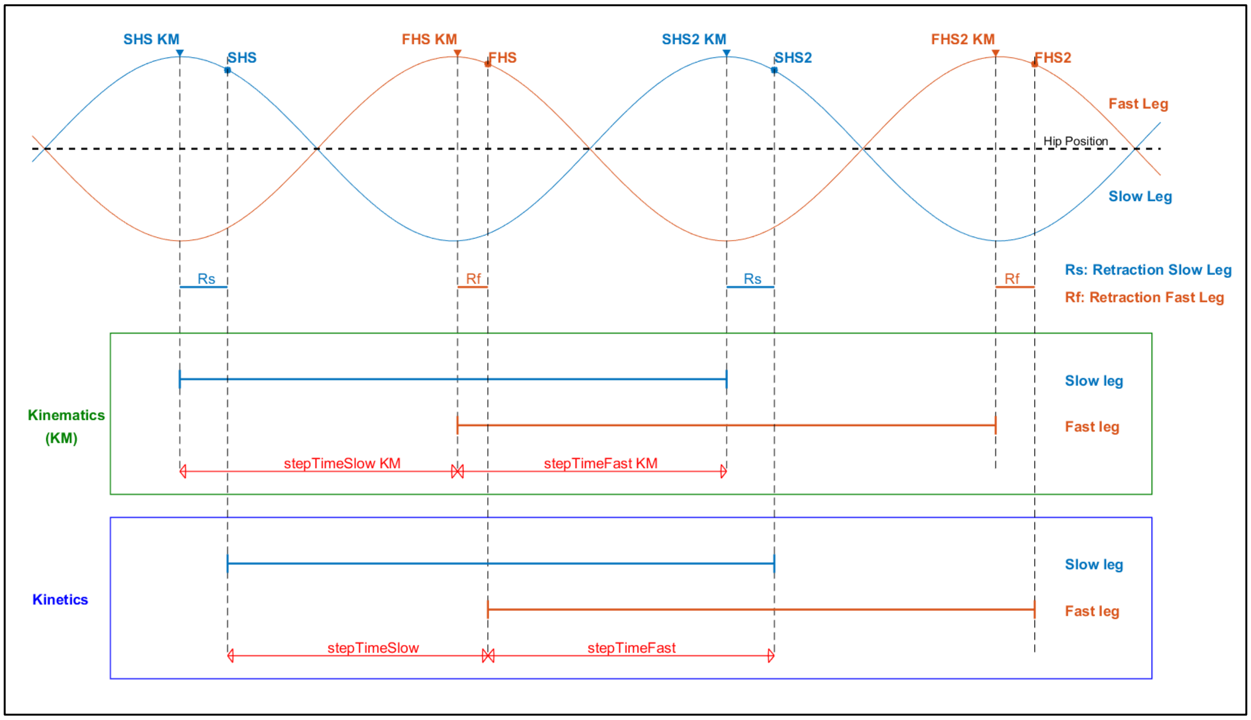

Figure 6: Simplified decomposition of event detection. The sinusoidal signals represent the transverse amplitude relative to the hip position. In the green and blue boxes, we describe how step times are computed when using kinematic and kinetic data, respectively. Actual ground contact i.e. heel strike always has a small delay with respect to the ankle maximum forward position (SHS kin and SHS), due to what we called retraction time.

The first way to detect event is using kinetic i.e. ground reaction forces recorded from the force plates. This is perhaps the most intuitive method, since it is easy to detect heel strikes (HS) and toe offs (TO) establishing a force threshold (in our case threshold is 30 N). Once we find the time and position of each HS and TO, it is now easy to calculate step times, step lengths, or any other parameter of interest. These kinetic events are represented in the blue box in Figure 6.

Another way to detect events is using kinematic data. The way we do this is taking leg angles (hip to ankle segment with respect to vertical) and finding the *minimas* and *maximas*. Therefore, the maximum forward position of the ankle with respect to the hip will be defined as the HS, and the maximum backwards position of the ankle with respect to the hip will be defined as the TO. These kinematic events are represented in the blue box in Figure 6.

As one may think that those two methods of detecting events would yield the same results, it is not that simple. This difference is not only due to the sampling difference between kinetics and kinematics (10 times higher for kinetics), but rather to some biomechanics constraints that become obvious once decomposition a stride cycle. We will discuss those differences in the results section.

2.3.3 Statistical analysis

A repeated measures two-way ANOVA was used to compare the effects of groups (i.e., control vs. temporal feedback) and condition (i.e., *TM base, EarlyAdapt, TM steady, AfterEffects*) on our outcome measures (e.g., all four contributions). Fisher's post-hoc testing was used when significant model effects where found from the two-way ANOVA. A significance level P = 0.05 was used for all analysis. Stata was used to perform all statistical analysis (StataCorp LP, College Station, TX). All the figures and plots presented in the results were done in MATLAB.

3.0 DATA ANALYSIS

3.1 PARAMETERS COMPUTATION

3.1.1 Parameters of interest

In order to interpret the data, and present coherent results, a list of parameters were computed. Let's establish a few definitions of the most basic ones, since they are arbitrary, and their definition can differ from study to study. All temporal parameters, which represent a time, expressed in (s), and spatial parameters, which represent a distance, expressed in (mm). Let's recall the important events from which all parameters will be computed: SHS, FHS, STO, FTO, and sometimes going to the next cycle, SHS2, FHS2, STO2 and FTO2. Ultimately, what we are interested in comparing is the subjects' asymmetry, since the rehabilitation processes work hard to get them back to symmetrical walking patterns. We define parameters to quantify temporal components, as well as spatial components. Step time of the fast leg (or *stepTimeFast*), is defined as the time from SHS to FHS, while step time of the slow leg – *stepTimeSlow* – is the time from FHS to SHS2. The sum of *stepTimeFast* and *stepTimeSlow* is therefore the stride time (SHS to SHS2). Step length of the fast leg (called *stepLengthFast*), is defined as the distance between ankle markers at FHS, and step length of the slow leg, or *stepLengthSlow*, is the distance between ankle markers at SHS2.

3.1.2 Step Length Asymmetry

It has been shown and widely accepted that gait can be decomposed in three main contributions. We will use the established definition of the parameter *netContribution* representing $(step\ length\ of\ the\ fast\ leg - step\ length\ of\ the\ slow\ leg)$ as a sum of three components, according to the literature. In order to be consistent with the literature, this will be called "Step Length Asymmetry".

$$netContribution = spatialContribution + stepTimeContribution + velocityContribution$$

Where

- $\underline{spatialContribution = spatialFast - spatialSlow = \Delta S}$

where *spatialFast* is the distance between ankle position of the fast leg at FHS and ankle position of the slow leg at SHS. *spatialSlow* is the distance between ankle position of the slow leg at SHS and ankle position of the fast leg at FHS

- $spatialFast = \alpha F - \alpha T$
- $spatialSlow = \alpha S - \alpha F$

Where

- αF is the maximum forward position of the fast leg at FHS
- αT is the maximum forward position of the slow leg at SHS
- αS is the maximum forward position of the slow leg at SHS2

<u>Note</u>: all positions are computed with respect to the hip position.

In order to be consistent with the literature, this will be called "Step Position"

❖ $\underline{stepTimeContribution = \Delta t * \bar{v}}$

Where $\Delta t = stepTimeFast - stepTimeSlow = time(FHS\ to\ SHS) - time(SHS2\ to\ FHS)$, and $\bar{v} = \frac{1}{2}(stepSpeedSlow + stepSpeedFast)$, where *stepSpeedSlow* and *stepSpeedFast* are the ankle speeds with respect to the hip, from ipsilateral HS to contralateral HS for the slow leg and the fast leg, respectively. In order to be consistent with the literature, this will be called "Step Time" (this will be used throughout the study, not to be confused with *stepTimeFast* and *stepTimeSlow* which are simply the time to take a step).

❖ $\underline{velocityContribution = \Delta v * \bar{t}}$

Where $\Delta v = stepSpeedSlow - stepSpeedFast$ and $\bar{t} = \frac{1}{2}(stepTimeFast + stepTimeSlow)$. We define step speeds (ankle speed with respect to the hip) the following way:

- $stepSpeedSlow = \frac{dispSlow}{stepTimeFast}$
- $stepSpeedFast = \frac{dispFast}{stepTimeSlow}$

Where

- $dispSlow = |(slow\ ankle\ position\ at\ FHS) - (slow\ ankle\ position\ at\ SHS)|$
- $dispFast = |(fast\ ankle\ position\ at\ SHS2) - (fast\ ankle\ position\ at\ FHS)|$

In order to be consistent with the literature, this will be called "Step Velocity".

If we use the same names used in the literature to quantify step asymmetry, $netContribution = spatialContribution + stepTimeContribution + velocityContribution$ now becomes

$$Step\ Length\ Asymmetry = Step\ Position + Step\ Time + Step\ Velocity$$

Since we are interested in studying the stride-by-stride evolution of those parameters, and each stride length is different, we normalize these parameters by the sum of step lengths. This new parameter is:

$$netContributionNorm2 = \frac{netContribution}{\sum(stepLengthSlow + stepLengthFast)} = \frac{netContribution}{\sum SL}$$

And of course the sum is also normalized, and becomes:

$$\begin{aligned} netContributionNorm2 \\ &= spatialContributionNorm2 + stepTimeContributionNorm2 \\ &+ velocityContributionNorm2 \\ &= \frac{\Delta S}{\sum SL} + \frac{\Delta t * \bar{v}}{\sum SL} + \frac{\Delta v * \bar{t}}{\sum SL} \end{aligned}$$

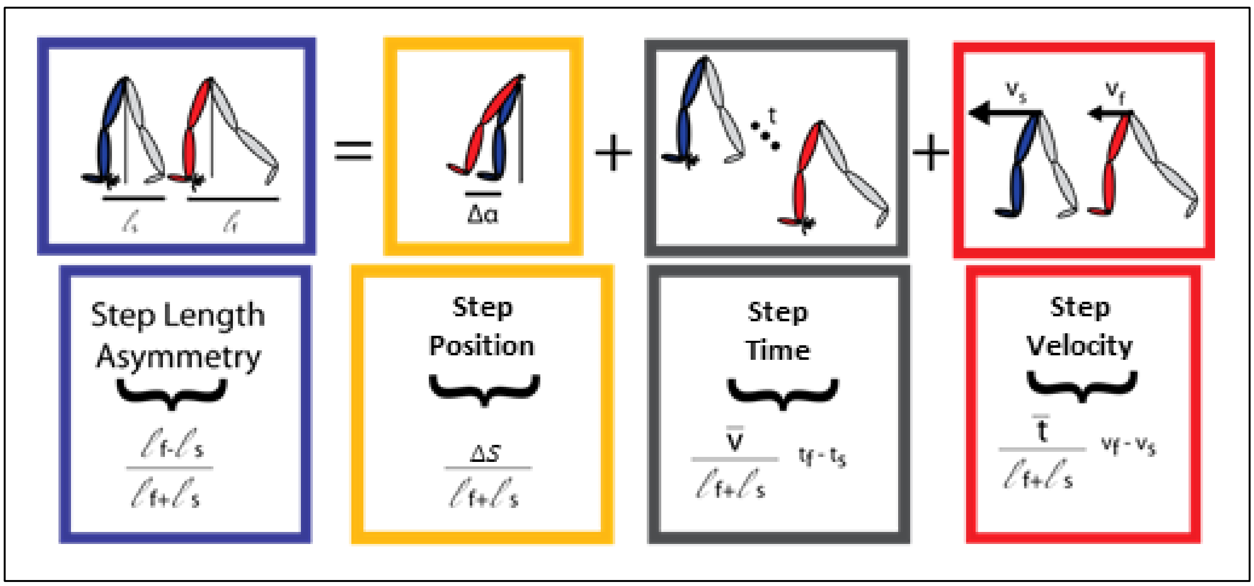

Figure 7: Schematics for Step Length Asymmetry decomposition. The blue and red legs represent the slow and fast legs, respectively; and l_f and l_s are the step lengths of the fast and slow leg, respectively. The yellow box shows the step position contribution (*where* to step); the black box shows the step time contribution (*when* to step) and the red box shows the step velocity contribution.

3.1.3 Leg velocities

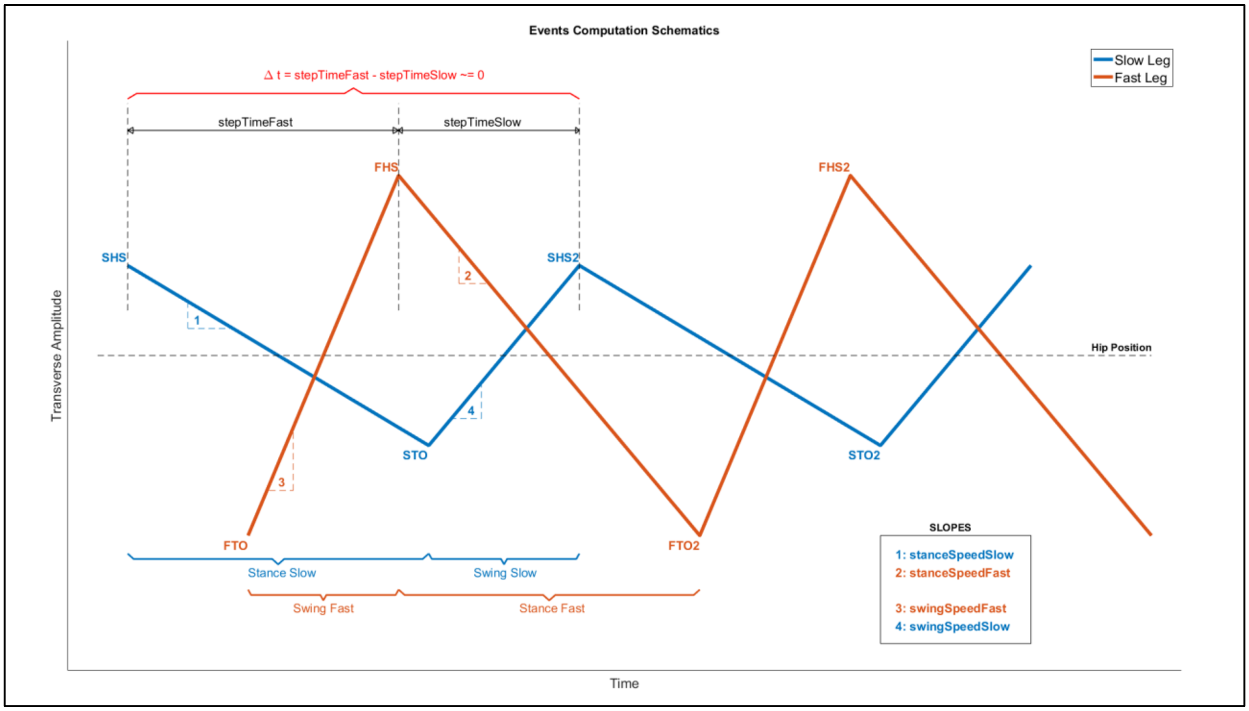

Figure 8: Schematic explanation of how step times can be modified. Amplitudes are represented as lines, to point out that we are talking about speeds (in reality they are sinusoidal signals). Hip position is represented as a straight line for simplification – in reality it is a sinusoidal signal with very small amplitude.

Figure 8 is a schematic representation of how step times are computed, representing the ankle amplitude in the transverse plane as a function of time. The fast leg is the leg corresponding to the fast belt, i.e. the dominant leg (in orange). Its amplitude is clearly larger than the small leg, since it's speed is twice as fast. The horizontal dotted line represents the mid-hip position. As defined earlier, we can see *stepTimeFast* (time from SHS to FHS), as well as *stepTimeSlow* (time from FHS to SHS2). Because of how it is defined, *stepTimeFast* is equal to the stance time of the slow leg minus the double support time (time from FHS to STO). The slow leg is being moved at half the speed of the fast leg. Therefore, the stance time of the slow leg is constantly larger than the stance time of the fast leg (more time spent on the leg that moves slower), which leads to *stepTimeFast* being larger than *stepTimeSlow*. Therefore, any temporal asymmetry is due to this step time difference. Figure 8 helps understanding how these two parameters can be modified during gait by changing four newly defined parameters.

- $stanceSpeedSlow$: Distance difference of the slow leg's ankle marker between SHS and STO, divided by the time from SHS to STO. In this figure, corresponds to slope 1.
- $stanceSpeedFast$: Distance difference of the fast leg's ankle marker between FHS and FTO2, divided by the time from FHS to FTO2. In this figure, corresponds to slope 2.
- $swingSpeedSlow$: Distance difference of the slow leg's ankle marker between STO and SHS2, divided by the time from STO to SHS2. In this figure, corresponds to slope 4.
- $swingSpeedFast$: Distance difference of the fast leg's ankle marker between FTO and FHS, divided by the time from FTO to FHS. In this figure, corresponds to slope 3.

3.2 EPOCHS OF INTEREST

The goal of the familiarization trial was only to get subjects used to the visual biofeedback. Since the target given was the mean of their normal walking pattern at baseline speed, subjects of the temporal feedback group showed the same behavior during baseline and familiarization. For the control group, the behavior was obviously the same, since the trials were identical. Along the results interpretation, we define four area of interest that we will compare to each other, in order to best assess the subject's behaviors.

3.2.1 Baseline steady state

Baseline represents the subject's most natural way of walking at the given speed (in our case 0.75 m/s). Given the temporal feedback group's ability to reach targets accurately during familiarization, and recalling that the control group's familiarization trial was simply the same as baseline, we consider that at the end of familiarization, both groups have reached steady state for a tied-belt condition. Throughout the whole study, this symmetrical walking pattern will be considered as the subjects' walking reference. To quantify it, we take the last 50 strides of familiarization, to which we subtract the last 5 strides, in order to remove any effect due to the stopping of the belts. The mean of these 45 strides will be called *TM base*.

3.2.2 Early adaptation

Since different domains adapt at different speeds, it is important to find a way to quantify the first response to the introduced perturbation, at the beginning of adaptation. Since the first step tends to be very noisy (almost tripping, very small step length, etc.) across subjects, we remove the first stride. Since the temporal domain tends to adapt really fast to the perturbation, we only take the following 5 strides. The mean all those five strides will be used throughout the study to quantify the first reaction to split-belt condition, and will be called *EarlyAdapt.*

3.2.3 Adaptation steady state

During a split-belt trial, subjects have to learn a new walking pattern. Therefore, the steady state is only reached after being exposed to the perturbation for a long time. While the baseline steady state could be considered after 150 strides (since no adaptation is needed), the adaptation steady state is considered to be reached after only 600 strides. Just like in baseline, we quantify the steady state by taking the mean of the last 50 strides, after subtracting the last 5 strides. As in baseline's steady state, this value will be called *TM steady.*

3.2.4 Early post-adaptation

The adaptation trial allows us to recreate new walking environments, and observe how subjects react to them. Therefore, during the post adaptation trial we can observe subjects' behavior right after being exposed to the perturbation. Since post adaptation is again a tied-belt trial, subjects should theoretically present the same behavior as observed during baseline. However, since they adapted to the split-belt condition, this tied-belt condition now feels like a new environment. The first few steps of post adaptation allow us to quantify the effects of the perturbation on the initial pattern, comparing how different they are from baseline. This could represent the amount of “learning” that the subject retrained from the experiment. Similarly, we take mean of the first 5 strides after removing the very first stride. This value will be called *AfterEffects*.

3.3 SAFETY HANDRAIL

All subjects were asked not to touch or hold the handrail, unless they felt like they were going to fall. As the experimental paradigm includes two sudden changes from tied belt to split belt condition and back, it can be hard to stay balanced without holding yourself. However, walking patterns can be significantly affected when adding an external reference.

3.3.1 Holding

Holding can simply be defined as any touching with a recorded force higher than the light-touching threshold. Since all step with recorded light-touching were considered as bad, it seems obvious that step with recorded holding were considered bad as well. Studies have shown that holding (applied force > 5 N) significantly modifies stride time and stride length parameters. Therefore, all steps where subjects were holding on to the handrail were remove from the analysis in the post processing of the data.

3.3.2 Light-touch

Light-touch is defined as applying a low force on a solid, static reference, with an arbitrary threshold set between 1 and 5 N. Some studies show that when setting the threshold at 5 N, light-touching doesn’t affect stride time or stride length. Other studies set a lower threshold of 1 N, showing that light-touching can affect step duration, as opposed to no touching at all.

In order to remove effects due to light-touching, files were post processed, taking into consideration the force applied to the handrail. Computing the mean force (all three directions), each step with a recorded force superior to 1 N was considered as a light-touch step, labeled as bad, and therefore was removed from the analysis. This allows us to attribute all changes and adaptation patterns to the studied motor outputs, removing external factors.

Table 4 summarizes the step that were removed due to holding or light touching. The mean is high because one of the first subjects (ST05) had a large number of steps removed (152). This was in the early stage of testing when we had not yet identified the negative effect of holding. All subjects after this one had less than 10 steps removed. Mean* is the mean of all subjects minus ST05 – much lower.

Table 4: Count of steps removed due to light touching or holding throughout all 4 trials.

COUNT OF STEPS REMOVED DUE TO LIGHT-TOUCHING / HOLDING

SUBJECTS	MEAN	MEDIAN	MEAN*
14	18.7	7	5.6

4.0 RESULTS

4.1 STEP TIME

4.1.1 Temporal feedback group adapts back to baseline behavior

The first noticeable and perhaps most important observation is that the temporal feedback group adapts its temporal contribution back to baseline behavior. In Figure 9 we can see that “TM base” and “TM steady” are non-significantly different (P=0.45) for the temporal feedback group. This is what we wanted to achieve using the temporal feedback, meaning we removed the temporal asymmetry. Let’s note that the control group reaches a steady state at the end of adaptation statistically different from its baseline steady state (P=0.001). This finding shows that once subjects have adapted to the perturbation, they can actually reach perfectly symmetrical step timing, if given the right instructions. In addition to this, we can see that the control group shows none significantly difference between “EarlyAdapt” and “TM steady”, suggesting that without the help of the temporal feedback, subjects don’t really adapt in the temporal domain. In other words, step timing can be voluntarily and consciously modified in a new environment, to counteract the fact that your legs are forced to move at different speed.

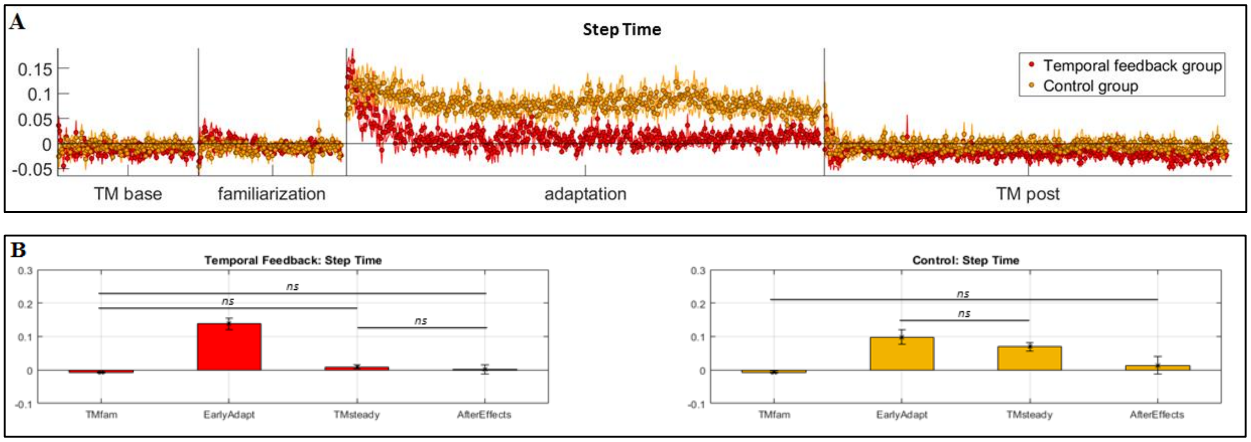

Figure 9: Step Time results. Figure A shows Step Time (*stepTimeContributionNorm2)* for both groups, through all conditions. Figure B is a statistical analysis of all conditions, within groups. "*ns*" indicates no significant different between conditions.

4.1.2 No lasting AfterEffects are observed

Another interesting finding is the absence of temporal aftereffect. We can see from Figure 9 that “TM base” and “AfterEffects” are not statistically different for Step Time, in both the temporal feedback and the control group. Figure 10 presents a zoom on the last steps of adaptation and the first steps of post-adaptation. Arguably, a small transient behavior could be observed, however the baseline behavior is reached again in less than 6 steps (since AfterEffects are not statistically different from baseline). Seeing how short the aftereffects are, and based on statistical analysis, we will consider from now on that there are no temporal aftereffects.

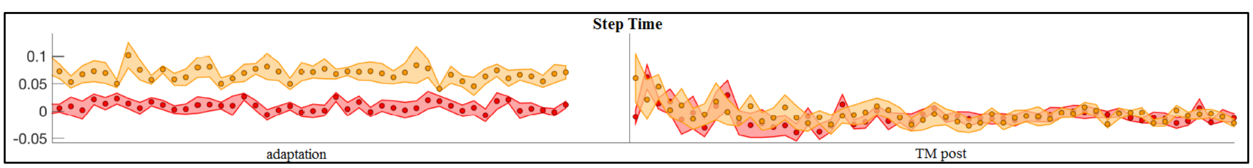

Figure 10: Step Time at the end of adaptation and beginning of post-adaptation zoom

Interestingly, this finding contradicts previous studies who quantify temporal aftereffects. Gait parameters are most commonly computed using kinematic data. We show here that when such parameters are computed using kinetic data, we find no aftereffects in the temporal domain. This suggests that even though the perturbation forces subjects to learn new walking patterns, their step timing is not altered when going back to baseline. Large aftereffects observed in other studies would therefore be due to kinematic adaptation rather than an actual time stepping adaptation. In other words, temporal aftereffects are not a “rhythm” re-adaptation (i.e. when the heel strikes actually happen), but rather a walking pattern re-adaptation (i.e. their rhythm is the same but the legs move differently during swing time). We verified these findings by computing parameters using both kinetic and kinematic data sets. Just like previous studies, we observed large aftereffects in the temporal domain when using the kinematic data. We will talk later in this section how there can be such a big difference between results, and how it can be explained. However, since our main analysis uses kinetic data recorded from the force plates, we can consider form now on that there are no aftereffects in the temporal domain.

Another very important conclusion to be drawn from Figure 9 and Figure 10 is the fact that the temporal aftereffects observed are the same for both groups (P=0.542). Changing step times in the temporal feedback group, we would have expected to see an influence on the aftereffects.

From these two findings, we can establish two important conclusions. Firstly, subjects present the same behavior at the end of adaptation and in post-adaptation, suggesting that nothing that they learned temporally in the new walking environment stayed when going back to a tied-belt condition. Secondly, no matter what the behavior at the end of adaptation was, the aftereffects are the same, confirming that there is no learning from one trial to another.

4.1.3 How do temporal contributions go down to zero?

If we consider baseline, a tied belt condition where no asymmetry can be observed, the steady state of this variable tends to zero. As discussed previously, we have shown that the temporal feedback allows to adapt back to baseline behavior during adaptation. Therefore, the steady state of the temporal feedback group during adaptation tends to zero as well. Let’s recall a previously established definition:

$$stepTimeContributionNorm2 = \frac{\Delta t * \bar{v}}{\sum SL}$$

From this equation, we see that if

$$\lim_{n \to steady\ state} stepTimeContributionNorm2 = 0$$

Therefore, it means that

$$\lim_{n \to steady\ state} \Delta t = 0 \qquad \textit{(1)}$$

<u>Note</u>: $\bar{v}\ or\ \sum SL$ might change the value of $stepTimeContributionNorm2$ but they won't bring it down to zero. The mean step speed $\bar{v}$ has values ranging between 650 and 700 mm/s, and the sum of step length $\sum SL$ has values ranging between 350 and 500 mm, therefore the ratio $\frac{\bar{v}}{\sum SL}$ is between 1 and 2 during the whole experiment. This confirms the veracity of equation *(1).*

Figure 11 shows that in order to adapt back to a baseline behavior, subjects minimize their step time difference (note that there are actual step times, defined as ipsilateral HS to contralateral HS, not to be confused with stepTimecontributionNorm2 also called Step Time), which is exactly what we were trying to achieve with the temporal feedback given. We can see that as expected, subjects will reduce their $stepTimeFast$, and increase their $stepTimeSlow$, in order to equalize them, reducing Δt. The bar plot on the right side of Figure 11 shows the steady states of each parameter at the end of adaptation, proven to be non-significantly different (P=0.414).

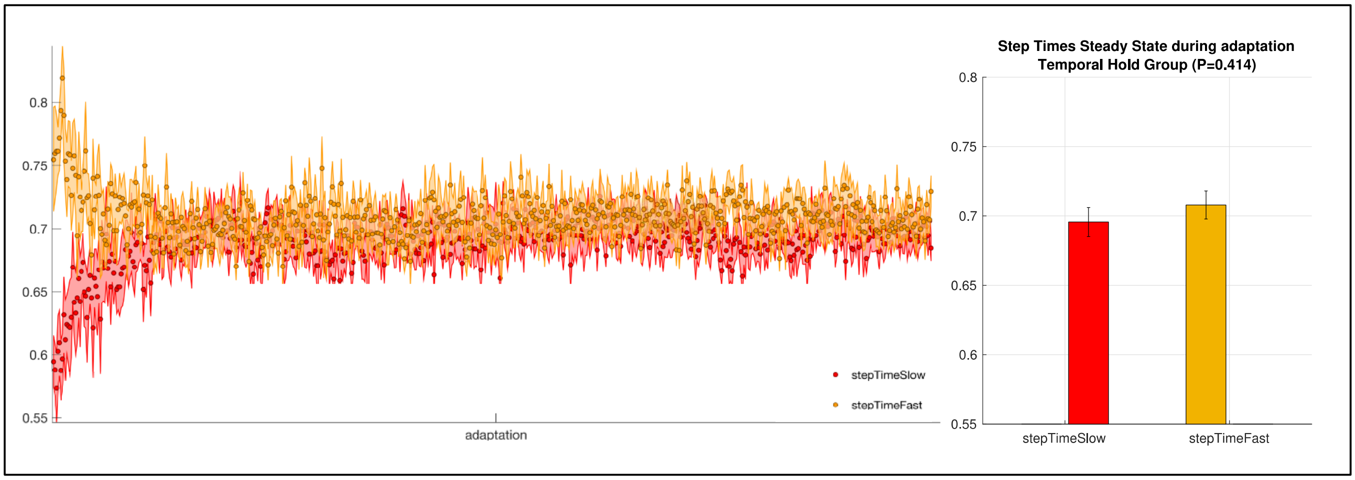

Figure 11: Step times evolution during adaptation for the temporal feedback group, in seconds. Bar plot indicates the steady state of adaptation with standard error.

4.1.4 Early adaptation

From Figure 9 we can see that temporal EarlyAdapt are slightly higher for the temporal feedback group than for the control group. This comes from a difference in step times at the between of adaptation between both groups. The temporal feedback group reduces *stepTimeFast* and increases *stepTimeSlow*, while the control group slowly increases both, keeping the difference constant. Therefore, for the first few steps, the step time difference is larger for the temporal feedback group, before a same steady state is reached. However, this difference only lasts for 8 strides, and EarlyAdapt values are not statistically different between groups (P=0.066), so this was not further considered.

4.2 STEP VELOCITY

4.2.1 How do velocities affect step times?

We have shown that we managed to successfully achieve one of our main objectives of this study, namely making subjects voluntarily change their stepping times. From 3.1.3 we have seen that the step time difference can be altered changing leg velocities.

Table 5: Velocity parameters used to modify stepping times. Each of these parameter's variations (↗: increase, ↘: decrease, with the use of the temporal feedback) would reduce the step time difference in one stride cycle

	STANCE SPEED	SWING SPEED
FAST LEG	$stanceSpeedFast$ ↘	$swingSpeedFast$ ↗
SLOW LEG	$stanceSpeedSlow$ ↗	$swingSpeedSlow$ ↘

Table 5 presents a summary of the available options to reduce the step time difference, which we is defined as $\Delta t = stepTimeFast - stepTimeSlow$. Therefore, in order to achieve $\Delta t = 0$, subjects can either make $stepTimeFast$ shorter, or $stepTimeSlow$ longer. For example, if $swingSpeedFast$ increases then FHS occurs sooner and then $stepSpeedFast$ would be shorter. Similarly, if $swingSpeedSlow$ decreases then SHS2 would occur later, lengthening $stepTimeSlow$.

4.2.2 Only the slow leg velocities are affected

Now that we have identified how subjects reduced their step time differences, we computed and plotted the four parameters discussed in section 4.2.1. A summary of the speeds of interest during adaptation can be found in Figure 12. On the right side of Figure 12, the bar plots show the steady states of each parameter and each group, as well as the standard error and P-values. The two groups only reach significantly different steady states for *stancespeedSlow*. Even though steady states are not significantly different for *swingSpeedSlow*, we can also see a small difference on the time plot.

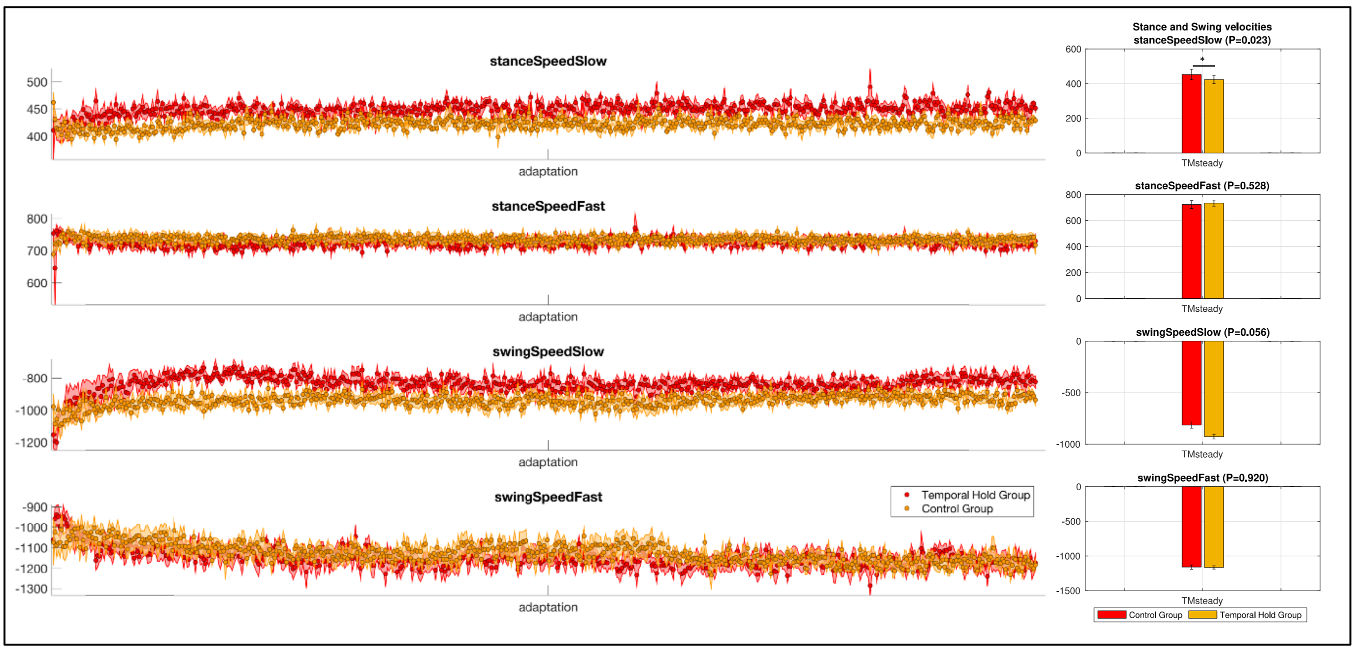

Figure 12: Swing and stance speeds for slow and fast legs during adaptation. Bar plot indicates the steady state of adaptation with standard error.

An interesting finding observed here is the fact that the fast leg speeds are not affected by the temporal feedback. Therefore, the temporal feedback only affects the slow leg's speeds. It's important to note that these velocities are computed for each leg independently, for the swing and stance phase.

4.2.3 Temporal feedback allows to internally reduce the perturbation

We have established that the temporal feedback leads to a change of stance and swing velocities. While it could be easy to assume that step speeds and stance speeds are the same quantities, they are not. Step speed represents the speed from ipsilateral heel strike to contralateral heel strike, while stance speed is actually the speed from ipsilateral heel strike to ipsilateral toe off. Therefore, the distances covered during these events are not the same. On top of that, step speeds are computed during step times, while stance speeds are computed during stance times. Stance time represents step time plus the double support time until toe off. We can see in Figure 13 that TM steady for Step Velocity is significantly lower for the temporal feedback. Since both groups are walking at the same belt speeds, exposed to the same perturbation, we were not expecting to see a difference here. Let’s study how the temporal feedback affected Step Velocity.

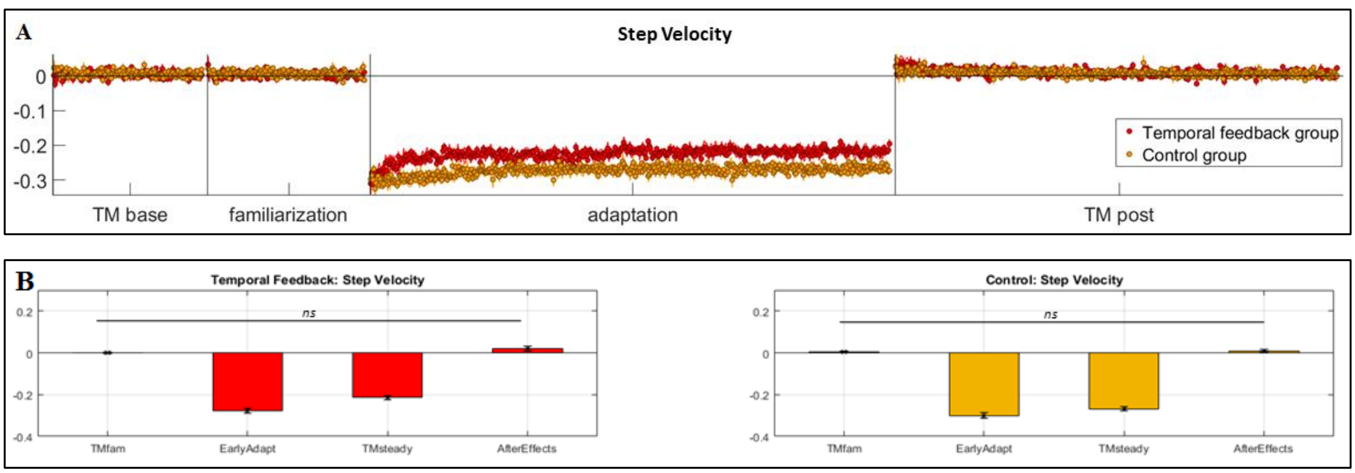

Figure 13: Step Velocity results. Figure A shows Step Velocity (velocityContributionNorm2) for both groups, through all conditions. Figure B is a statistical analysis of all conditions, within groups. "ns" indicates no significant different between conditions.

The first step to studying $velocityContributionNorm2$ is making sure that the changes are actually due to Δv, and not due to the $\frac{\bar{t}}{\sum SL}$ ratio. When examining this ratio’s steady state at the end of adaptation, we see no statistical difference between groups (P=0.438).

Therefore can consider that the changes in $velocityContributionNorm2$ from one group to another are entirely due to Δv. Let's note that Δv is the step speed difference between legs, which essentially represents the induced perturbation. The spit-belt conditions have the objective of altering this speed difference. Hence, Δv is actually the best way to quantify the "amount of perturbation" that we introduced to the subjects. In the literature, $velocityContribution$ is often referred to as "perturbation".

Figure 14 shows step speeds plotted for both groups, along with statistical analysis between steady states, and we can appreciate the predicted changes. For both $stepSpeedSlow$ and $stepSpeedFast$, steady states are significantly different between groups.

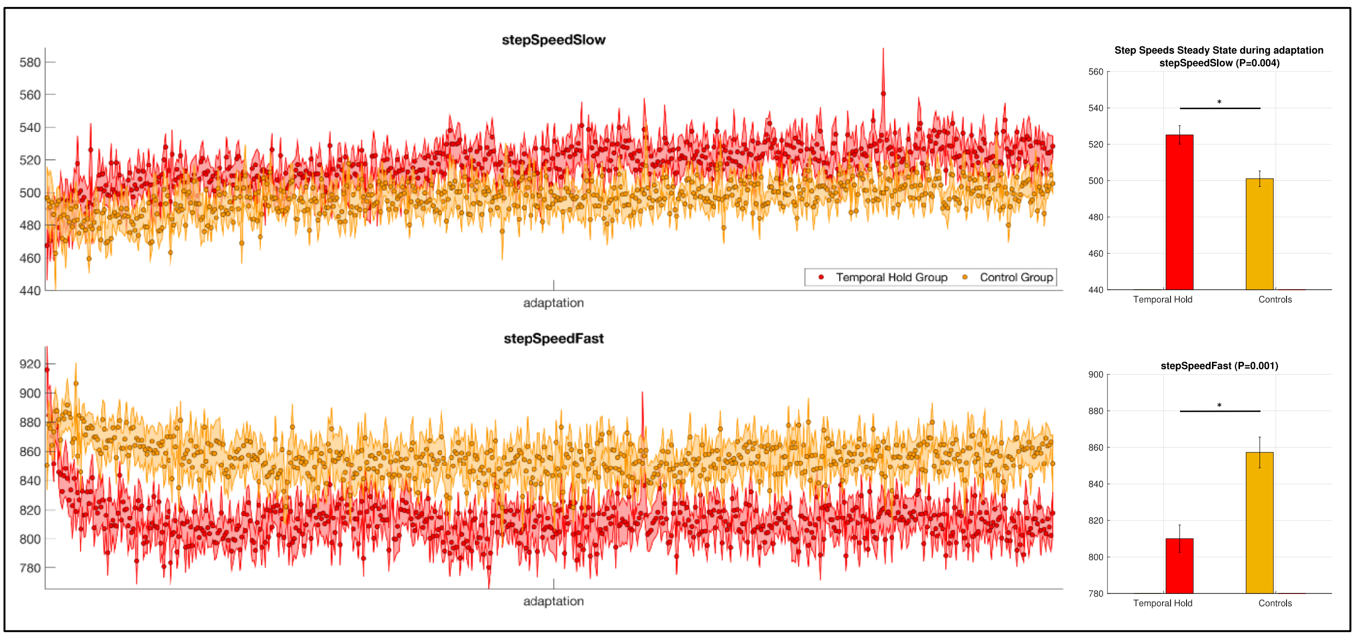

Figure 14: Step speeds for both legs and both groups. Bar plot indicates the steady state of adaptation with standard error with P-values.

Looking at Figure 14, we see that the increase in $stepSpeedSlow$, and decrease in $stepSpeedFast$ lead to a reduction of Δv. Considering the fact that Δv is the amount of perturbation introduced, what does this mean? This means subjects adapt their stepping speeds to "counteract" the perturbation, in order to feel like they are less perturbed. We could talk of an "internal" speed adaptation, since all subjects were exposed to the same belt speeds.

Note: it can be surprising that even though we established that the temporal feedback had an effect only on the slow leg's velocities, we can see a change for $stepSpeedFast$. This comes from the fact that $stepSpeedFast$ is computed from parameters from both legs ($dispFast$ and $stepTimeSlow$). Since the temporal feedback doesn't affect $dispSlow$ and increases $stepTimeSlow$, $stepSpeedFast$ decreases (see definition). Similarly, the temporal feedback forces $dispSlow$ to increase, while decreasing $stepTimeFast$, leading to a decrease in $stepSpeedSlow$.

4.3 STEP POSITION AND STEP ASYMMETRY

4.3.1 How does the temporal feedback affect the spatial domain?

We have established that the temporal feedback reduces subject's step speed difference in the previous section. As seen in Figure 11, at the end of adaptation, step times are the same for each leg in the temporal feedback group. Since the step speeds are different, we can therefore predict that the temporal feedback induces a spatial change as well.

We can see from Figure 15 that spatial contributions (step lengths) are affected by the temporal feedback. Similarly to the velocity contributions, however, we observe changes between groups only for the slow leg. Subjects from the temporal feedback group do not see a change in their fast leg's step lengths, however they consistently take longer steps with their slow leg.

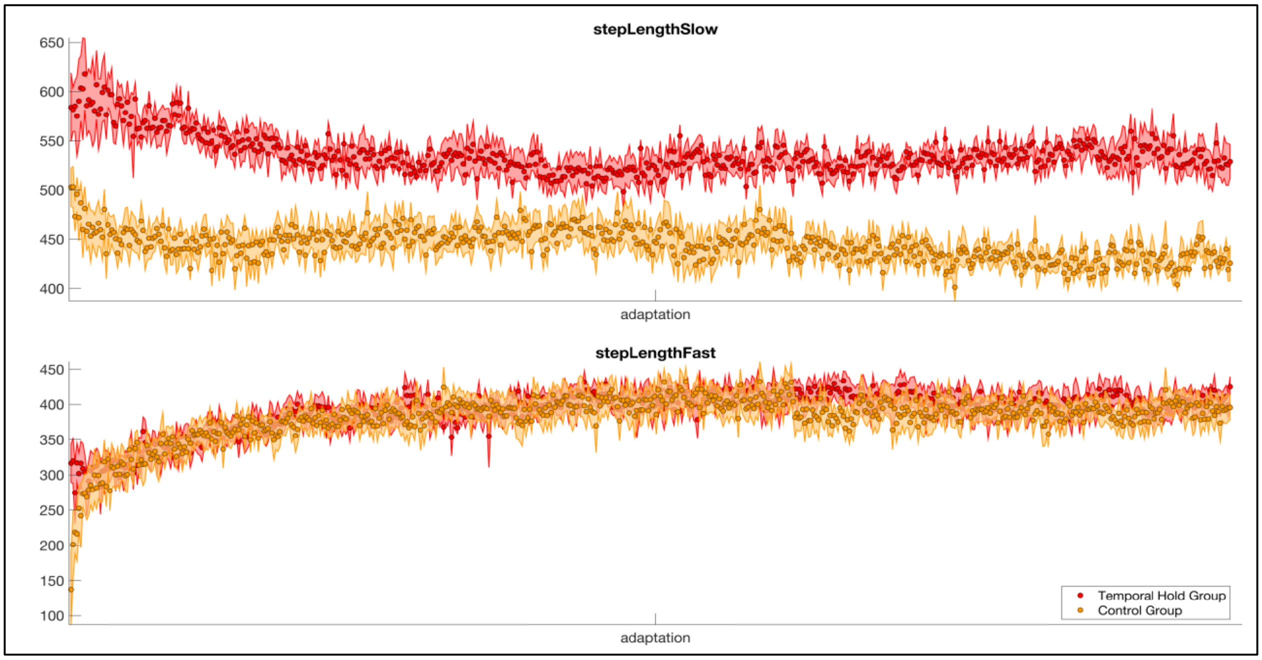

Figure 15: step lengths vs strides during adaptation trial, for both temporal feedback and control groups.

4.3.2 Temporal feedback group spatially adapts back to baseline behavior in adaptation

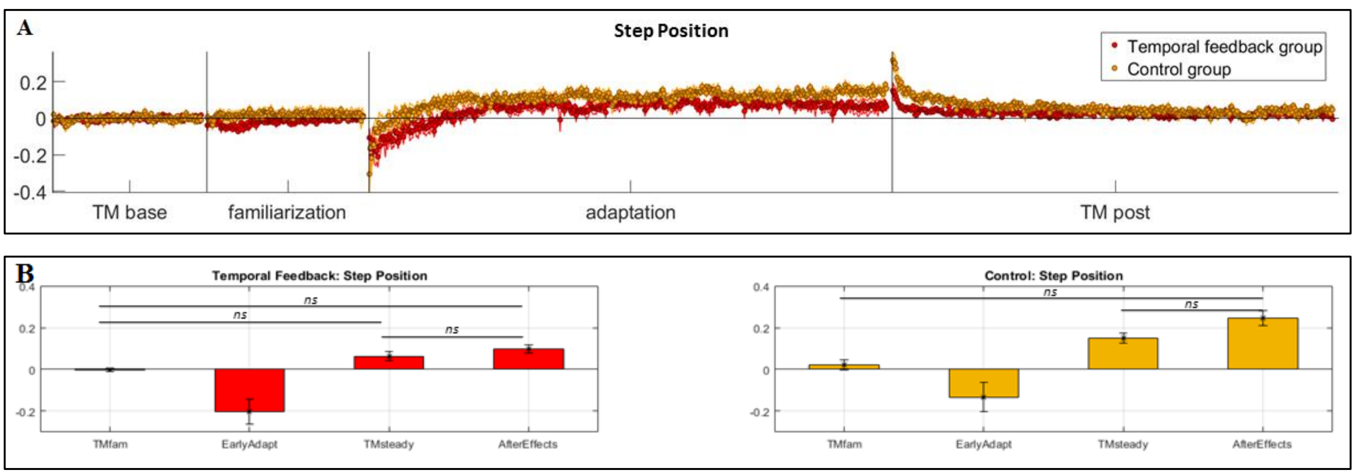

Figure 16: Step Position results. Figure A shows Step Position (spatialContributionNorm2) for both groups, through all conditions. Figure B is a statistical analysis of all conditions, within groups. "ns" indicates no significant different between conditions.

We now know that subjects from the temporal feedback group will voluntarily take longer steps (spatially) with their slow leg. In other words, their maximum forward amplitude is larger for the slow leg, i.e. the temporal feedback increases $\alpha S\ and\ \alpha T$. The forward amplitude of the fast leg is consistently larger than the one of the slow leg, i.e. αF is larger than $\alpha S\ and\ \alpha T$. On top that, the temporal feedback doesn't change the fast leg's step lengths, therefore αF stays constant across groups. Given their definition, we can conclude that the use of the temporal feedback will decrease $spatialFast$ (αF doesn't change, αT increases), and increase $spatialSlow$ (αS increases, $\alpha F > \alpha S$). Therefore, $spatialContribution$ steady state at the end of adaptation is lower for the temporal feedback group than for the control group. Step Position is even lower since we normalize by the sum of step lengths, which is higher for the temporal hold feedback.

These changes in step lengths explain how the temporal feedback indirectly affects the spatial domain to adapt back to baseline behavior (as seen in Figure 16).

Note: Computed parameters $dispSlow$, $dispFast, spatialSlow\ and\ spatialFast$ may seem very specific but they have been defined and accepted in the literature. $stepLengthSlow$ and $stepLengthFast$ are the general definition of step length; $spatialSlow\ and\ spatialFast$ are the ankle distance forward with respect to the hip position; and $dispSlow$ and $dispFast$ are the distance covered by each individual ankle during a step. Figure 17 graphically illustrates how each spatial parameter in this study is computed, using limb angles.

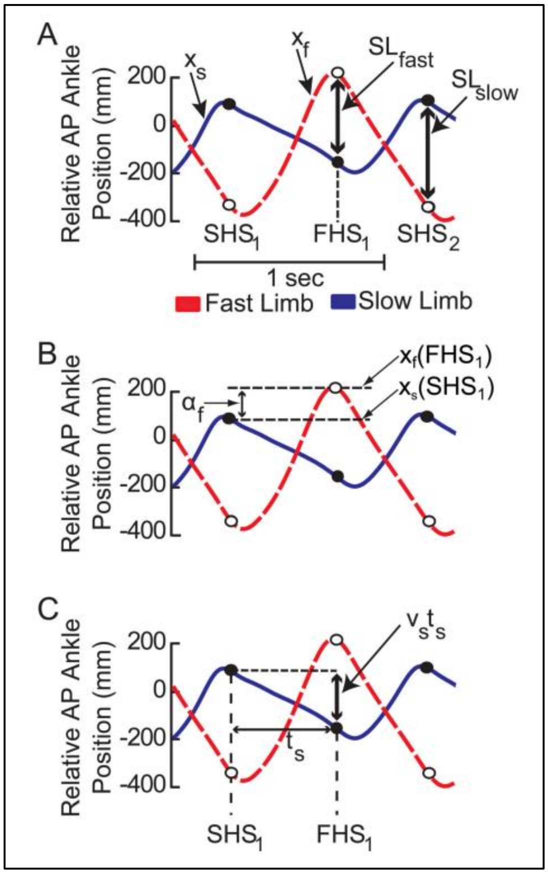

Figure 17: Graphical representation of the computed spatial parameters. Red and blue curves are the trajectories of the fast and slow leg respectively. Each plot illustrate how a parameter is computed. Plot A: $stepLengthSlow$ and $stepLengthFast$. Plot B: α_f is what we call $spatialFast$. $spatialSlow$ is not represented but would simply be $x_s(SHS_2) - x_f(FHS_1)$. Plot C: $v_s t_s$ is what we call $dispSlow$. $dispFast$ is not represented but would simply be $v_f t_f$. (Source: Finley and al., 2015)

4.3.3 Temporal feedback significantly reduces spatial aftereffects

In the control group, each change in belt speeds is perceived as a new perturbation. The subjects actually feel like they are exposed to two different perturbations: the first one being the adaptation split-belt trial, the second one being the post-adaptation tied-belt trial.

The temporal feedback's main effect is to suppress step time differences between legs, and as seen in 4.1.3 it leads to subjects walking symmetrically in the temporal domain. Another indirect effect is that it reduces the spatial contributions, making subjects walk symmetrically in the spatial domain. In both the spatial and the temporal domain, we observed an adaptation back to baseline behavior as a response to the temporal feedback, "counteracting" the perturbation. In other words, the perturbation is suppressed and subjects behave just like during baseline. Therefore, the change back to a tied belt trial doesn't present aftereffects, since it won't be perceived as a new perturbation.

4.3.4 Step Length Asymmetry

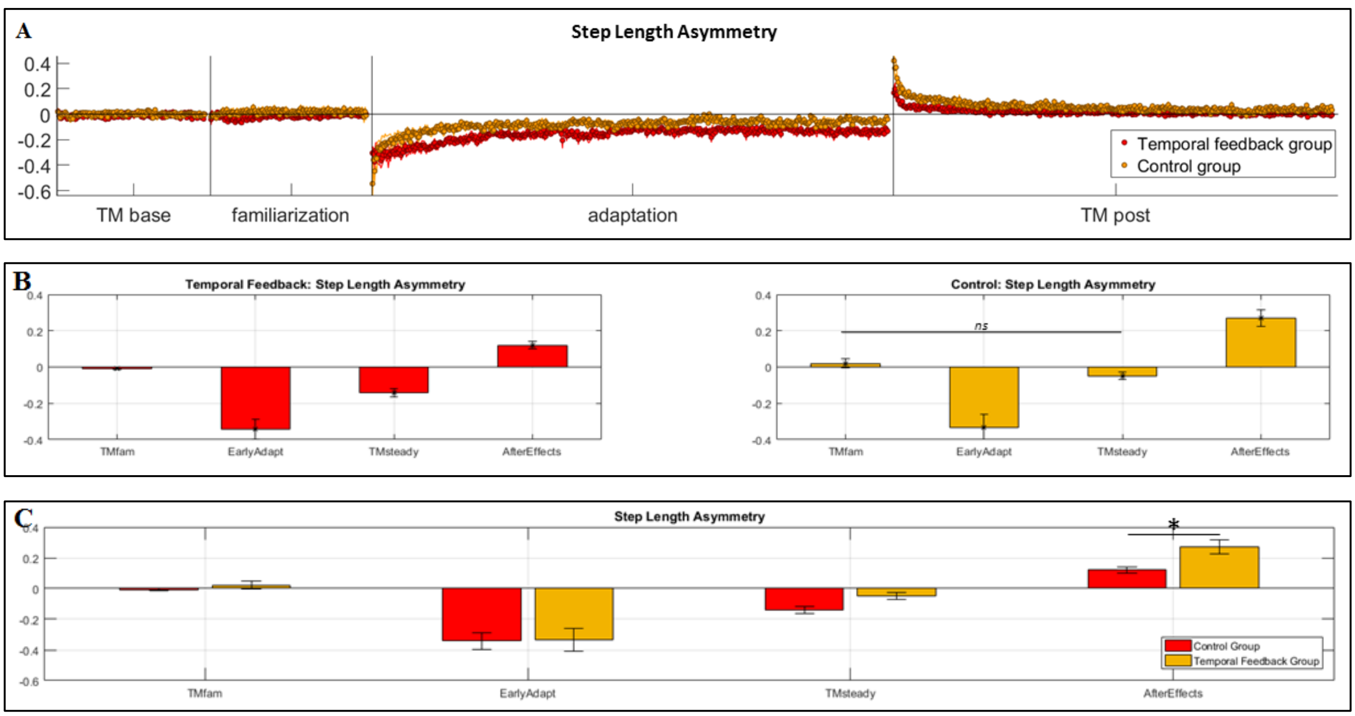

Figure 18: Step Length Asymmetry results. Figure A shows Step Length Asymmetry (netContributionNorm2) for both groups, through all conditions. Figure B is a statistical analysis of all conditions, within groups. "ns" indicates no significant different between conditions. Figure C shows statistics between groups for each condition. "*" indicates a significant difference.

From the definition of Step Length Asymmetry ($netContribution$) we know that this parameter is the sum of all three previous parameters and represents the subject's step length asymmetry. From Figure 18B, we can see that the control group was able to adapt Step Length Asymmetry back to baseline. The temporal feedback, though, disrupts this adaptation and subjects from the temporal feedback group reach a TM steady different from TM base. However, from Figure 18C we can see that TM steady is not significantly different between groups (P=0.104). This leaves the effect of temporal feedback on Step Length Asymmetry rather inconclusive for now.

One clear finding however is the face that the temporal feedback allows to significantly reduce the amount of aftereffects (P=0.01).

4.4 KINETICS VERSUS KINEMATICS: RETRACTION TIME ADAPTATION

4.4.1 EarlyAdapt and AfterEffects are different depending on the type of data used

As mentioned earlier in the discussion, we computed our parameters of interest with both kinetic and kinematic data. We noticed significant differences in the temporal domain between the two data sets. Findings from 4.1.2 show that there were no temporal aftereffects when using kinetics for event detection. As reported in the literature, we found significant temporal aftereffects when using the kinematic data to compute parameters. Time course of all contributions, for each group, can be found in Figure 19.

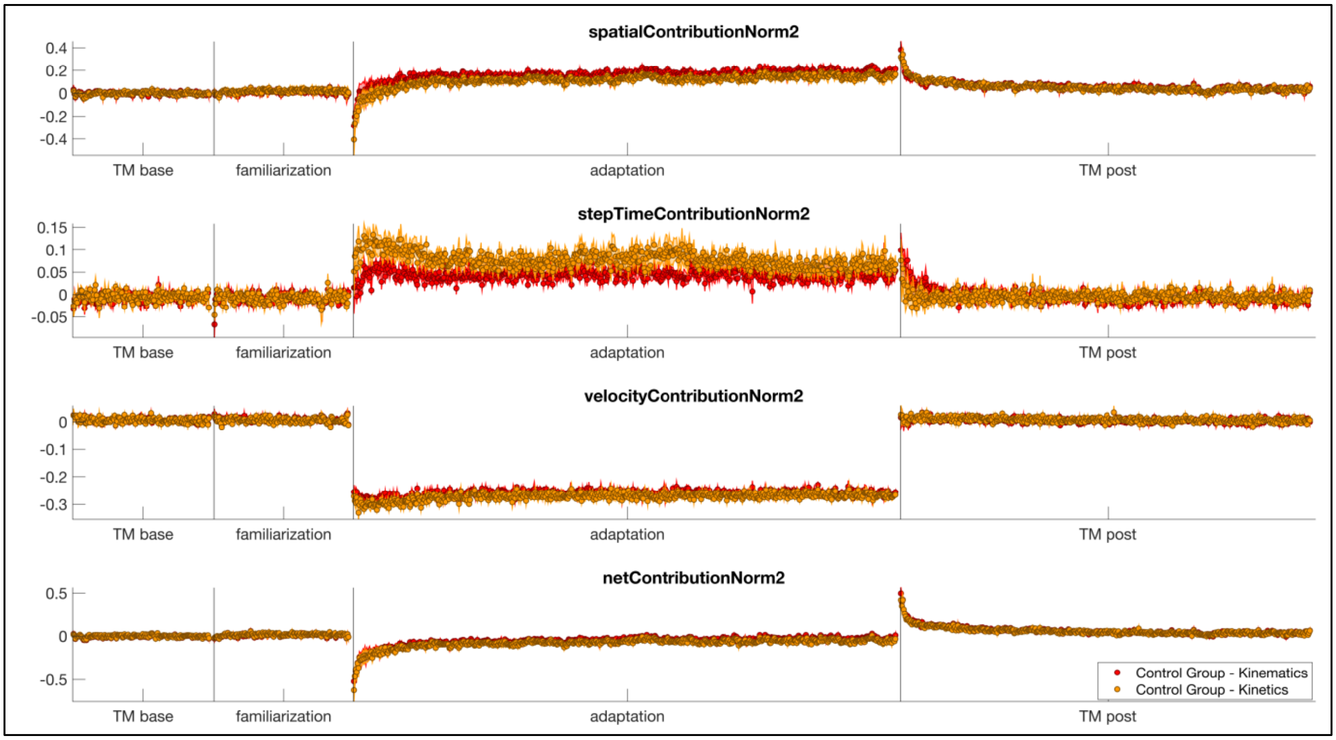

Figure 19: Contributions for the control group using both kinetic and kinematic data

In theory, these two methods of collecting data and computing parameters should yield the same results, since the same parameters are being measured. However, although the spatial and velocity contributions are the same, significant differences can be found between the two methods in the temporal domain. Adding them up to compute Step Length Asymmetry, we realize that they are not significantly different across groups. Still, this difference is important to understand and quantify, since it presents a major aspect of understanding how the temporal domain function, in both the kinetics and the kinematic domains. The statistic for these comparisons can be found in Figure 20.

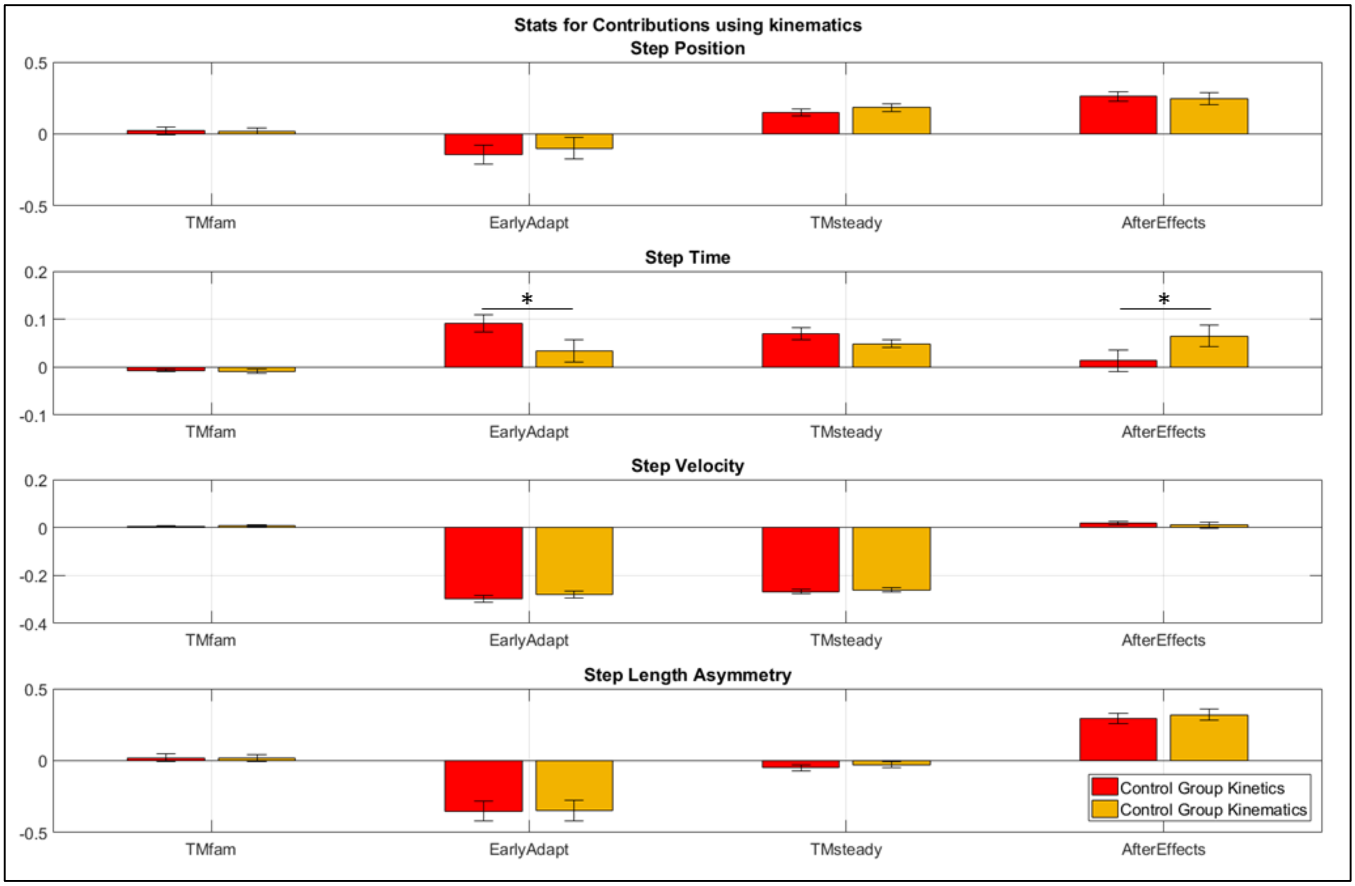

Figure 20: Statistical summary of all contributions for all conditions. We compare the kinetic and kinematic data sets, for the control group, used as a reference.

The next section addresses why there is a difference between those two data set, and why the contributions are only different in the temporal domain.

4.4.2 Retraction time

Figure 5 shows a summary of how parameters are computed using kinematics and kinetic data. In the green box, stride times are decomposed for each leg, to show step times calculation using kinematics (heel strikes defined as maximum forward ankle position with respect to hip position). In the blue box, we show step time calculation using kinetic (heel strike is the actual time when the foot hits the ground) time. R_S and R_f are the retraction times for the slow leg and the fast leg, respectively.

Now that we have decomposed how step times are computed, and defined the retraction time parameter, let's try to establish a mathematical model to explain how the two data sets differ. Let's call Δt^K the step time difference for the kinematic data, and Δt the step time difference for the kinetic data.

$$\begin{aligned}
\Delta t^K &= stepTimeFast^K - stepTimeSlow^K \\
&= \left(R_f + stepTimeFast - R_s\right) - \left(R_s + stepTimeSlow - R_f\right) \\
&= (stepTimeFast - stepTimeSlow) - 2 * R_f + 2 * R_s \\
&= \Delta t + 2 * \left(R_s - R_f\right) \\
\Delta t^K &= \Delta t + 2 * \Delta R
\end{aligned}$$

We can see that if R_s is constantly larger than R_f, then Δt^K will consistently be larger than Δt, and inversely. Our model suggests that this is where the difference between EarlyAdapt and AfterEffects comes from. The perturbations force a kinematic adaptation, which suggests to be represented by this model. Therefore, the retraction time of the fast leg, R_f, is larger than the one of the slow leg, R_s, during early adaptation, which explains why EarlyAdapt is higher using kinetic data. During the early post-adaptation, on the contrary, R_s is larger than R_f, leading to higher aftereffects when using kinematic data. Figure 21 is a plot of these time differences and retraction time difference that validates the model established.

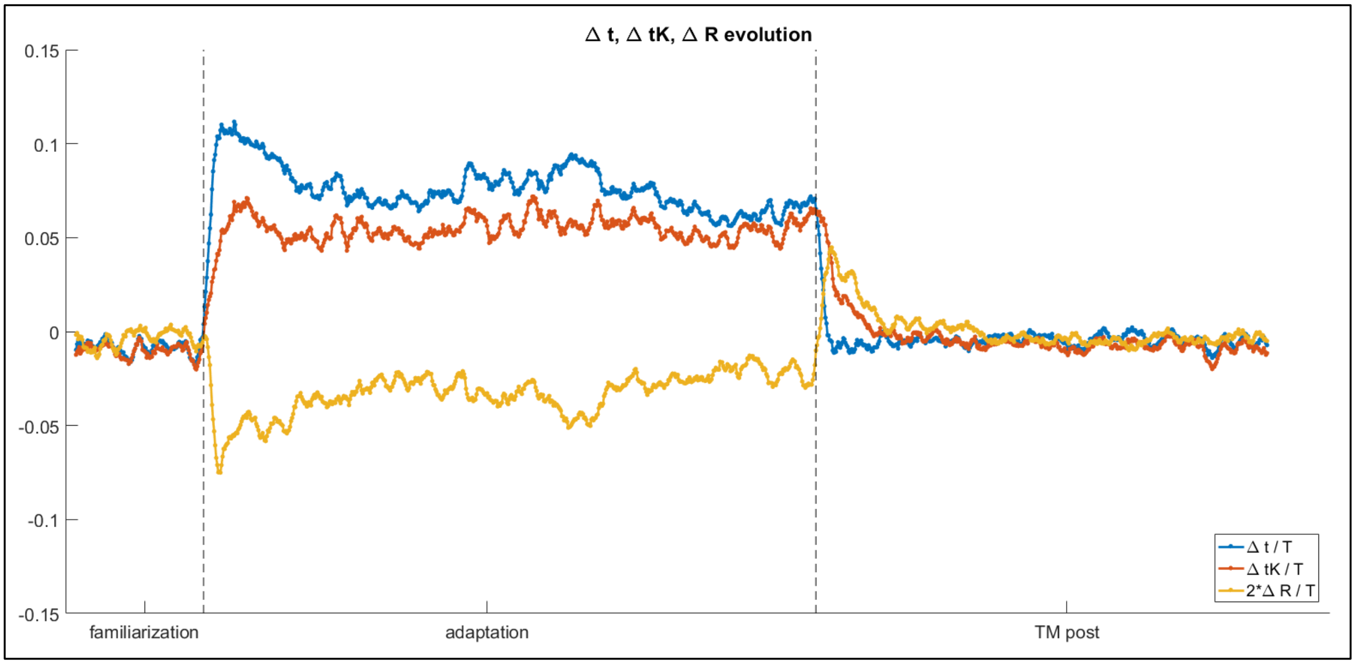

Figure 21: Graphic representation of the model explaining the difference between kinetic and kinematic data sets. Blue and orange curves are the evolution of the step time difference (throughout the last three trials) for the kinetic and kinematic data sets, respectively. The yellow curve is the evolution of the retraction time difference (multiplied by a 2 factor to satisfy the established model). Therefore, the orange curve is the sum of the blue and yellow curve.

<u>Note</u>: An important limitation to this simplified model, is the fact that the retraction times are not always the same. If we consider SHS to SHS2 to be an n^{th} stride cycle, then an more accurate model would be the following one.

$$
\begin{aligned}
(\Delta t^K)_n &= (stepTimeFast^K)_n - (stepTimeSlow^K)_n \\
&= \big((R_f)_n + (stepTimeFast)_n - (R_s)_{n+1}\big) - \big((R_s)_n + (stepTimeSlow)_n - (R_f)_n\big) \\
&= ((stepTimeFast)_n - (stepTimeSlow)_n) - 2 * (R_f)_n + (R_s)_n + (R_s)_{n+1} \\
&= (\Delta t)_n + \big((R_s)_n + (R_s)_{n+1} - 2 * (R_f)_n\big) \\
(\Delta t^K)_n &= (\Delta t)_n + (\Delta \tilde{R})_n
\end{aligned}
$$

Where

$$(\Delta\tilde{R})_n = (R_s)_n - 2 * (R_f)_n + (R_s)_{n+1}$$

Although we will not study this model further, it is important to acknowledge that this recurrence is a better representation of what actually happens.

5.0 DISCUSSION AND FUTURE WORK

This study was conducted to establish if the spatial and temporal contributions of gait can be controlled independently, using a specific condition of split-belt walking. The first question we had to answer was whether it was possible or not for humans to adapt their stepping times voluntarily. We showed that with the use of a visual temporal feedback, subjects were perfectly capable of reaching the targets they were given, adapting their step times. Therefore, the nervous system is able to be voluntarily manipulated to change step timing patterns. With the use of this temporal feedback, we also showed that we could "clamp" the temporal gait features, forcing subjects to suppress all step time asymmetries they would normally show in a split-belt condition, as seen in the control group. In other words, we were able to prevent subjects from adapting in the temporal domain, bringing the step time contribution to zero.

While modulating subject's step times, we wanted to see if the spatial contributions would be affected. We prove that the use of the temporal feedback affects subjects leg speeds, in order to "internally" reduce the felt perturbation. The subjects from the temporal feedback group adapted in order to feel less perturbed than the ones who were not given any feedback, which had the impact of lowering step position. When forcing subjects to reduce their stepping asymmetry with the use of the feedback, the slow leg counteracted by taking longer steps, and therefore reducing the step position contribution. This leads us to the conclusion that temporal gait features cannot be controlled independently from the spatial ones.

Regarding step symmetry, we proved that suppressing the temporal asymmetry leads the subjects to a larger step length asymmetry, showing that the spatial domain cannot compensate for the perturbation alone.

Future work that could be done would be to determine if it possible to set subjects' step time asymmetry to an arbitrary value for which the spatial gait features would be able to recover the step length asymmetry. Now that we know that humans are able to voluntarily change they step times, we could also test the visual temporal feedback on hemiparetic patients who present large temporal asymmetries. If they are able to complete this task – possible for humans – this could lead to promising rehabilitation processes to help recover temporal symmetry in gait.

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