École Polytechnique Fédérale de Lausanne

Gate analysis of SCI patients with and without EES stimulation in comparison to healthy subjects

Jade Therras, Lena Bribosia de Sepibus, Lucas Muespach, Mohamed Amine Ben Ahmed, Ananda Woltz,

INTRODUCTION

Walking is for most of us a natural and easy activity to engage in, a daily endeavor at which we do not even need to think about. But this apparently simple activity hides a range of complex kinetic features and muscle coordination. In patients with spinal cord injury (SCI), locomotion can be totally impaired, but it can be partially restored thanks to a new technology involving electrical epidural stimulation (EES) of the spinal cord. In this project, the gait pattern of three groups will be analyzed and compared with kinetic markers and EMG: healthy subjects, patients suffering from SCI with and without stimulation. Data was taken in the Courtine lab at the CHUV. Healthy participants were asked to walk on a treadmill at 1, 2 and 3 km/hour, with an additional round at 3km/h with a 20% inclination. The SCI was supported by an overground robot and was asked to walk 1 km/hour without EES, and then with a speed ramp from 1 to 2 and 3 km/h with EES. Kinetic markers were attached left and right to the hip, the knee, the ankle, and the toe, permitting a full reconstruction of the limb's movements. EMG was recorded for the following muscles: the iliopsoas, the biceps femoris (only left), the rectus femoris, the vastus lateralis, the tibialis anterioris, the semitendinosus, the medial gastrocnemius, and the soleus. Axes were defined as such: x is the lateral movement, y is the direction of displacement, and z points toward the ceiling.

Our project contains several matlab files.

In *exploration.m*, we explore the dataset and try some filter and gait detection methods. In *kinematic.m*, we implemented the gait detection methods. We visualize the gait detections and normal walking using plots and animation. In *gaitparameters.m*, we calculate gait parameters and did a PCA visualization. In *emgLib.m* are gathered all the functions needed to perform preprocessing as well as calculation of different EMG parameters.

`https://github.com/jadetherras/project_1_locomotion/tree/main`

GAIT EVENT DETECTION ALGORITHM AND VISUALISATION

Before computing gait parameters, it is necessary to extract the different gait cycles and gait events such as foot off and strike, in order to identify the stance and swing phases.
We first carefully observed the videos to develop an intuition of the more prominent aspects of walking, and used appropriated plots to help investigations. Then these observations were used to develop an automated algorithm that can detect these gate events. All code can be found in *exploration.m*

Generally, the axis of walking (y) seemed the most relevant. Toe patterns seemed the easiest and most precise to analyze while being a clear indicator of foot off and strike. As maximas and minimas are not smooth, we first filtered the signal using a low-pass filter (while being careful not to introduce any temporal delay that would shift the detection) to have an easier and more precise detection of them. After that, detection of foot off and strike (e.g. toe min and max in y) could be detected by taking the gradient of the resulting function and finding the zeros. A figure for ankle signal, pre and post-filtering has been done in fig. 1 This method provided general good results, but further exploration revealed data integrity problems with the toe, mainly in SCI, but also in healthy subjects. It was thus decided to only work with the ankle data, in the y and z direction (see. fig.2).

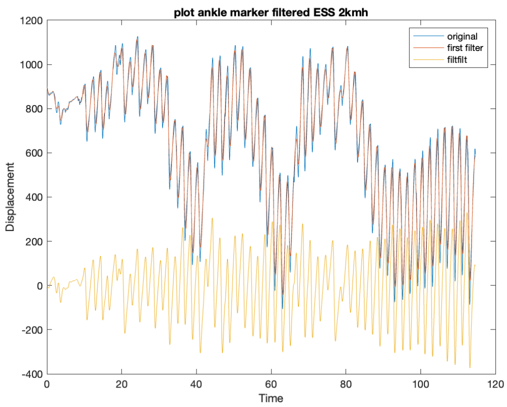


FIGURE 1
Pre and post filtering of kinematic signal in EES subjects

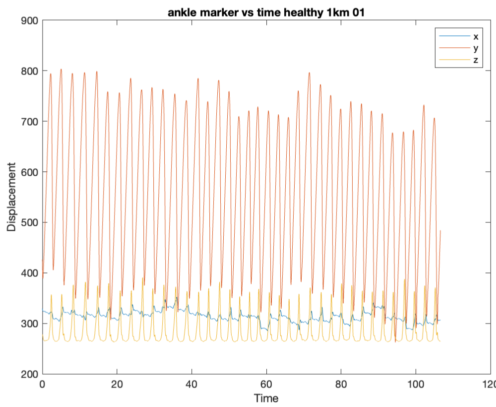


FIGURE 2
Ankle data in x, y and z for healthy subjects

For foot strike detection, it is naturally the timing where the ankle is the furthest in healthy subjects. But as SCI patients had a tendency to move it even more forward before striking the ground, an additional condition on the z-axis gradient stabilization was added. For the foot off, a similar thought was applied: when the ankle is the lowest in y, z gradient is monitored until it stabilizes, as the ankle is much accelerated just before the feet is lifted.

Additionally, to avoid wrong detection of gaits when, pattern that can arise especially in SCI, the leg swings back and forth while still being in the air, detection of foot off and strike has been made on the right and left leg, that must arise one after the other. In this way, we can make sure that every gait event happens in each computed gait.

To further verify the consistency of every gait, a histogram of every gate duration has been plotted to see if they had a natural distribution. Some outliers were observed (see fig. 3), and were thus removed from the parameter calculation (only gates with duration between 0.5 and 4s were kept). Additionally, step length must be greater than 88 to avoid registration of "mini-steps" of SCI patients when they are almost lifted and trying to regain balance before engaging again in more "normal" locomotion. (see fig. 4)

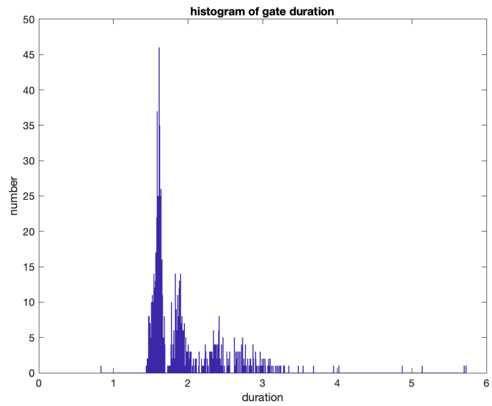


FIGURE 3
Gate duration distribution before constraint

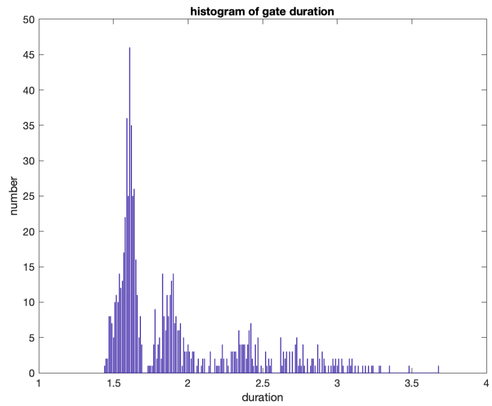


FIGURE 4
Gate duration distribution after constraint

Several steps were taken to confirm our algorithm (code can be found on *kinematic.m*). First, time matching with the visual detection markers on the video was made. This could give a general appreciation of the result, but was not very precise. Visualization of the markers - connected to simulate the limbs - has been made on the y-z plane and in time, with red and blue bars given by the algorithm at each event (see fig. 5), which readily confirmed good detection. We also animated the gait with the help of the markers, and implemented a signal whenever the foot went on 7 and off the ground 8 - which additionally confirmed our algorithm. The animation can be seen by running the *kinematic.m* script.

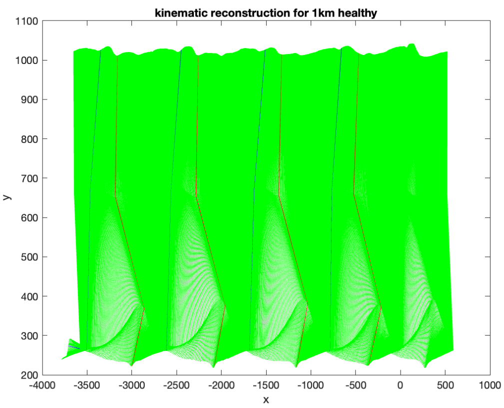


FIGURE 5
Foot off and strike event in healthy subject for the right limb, marked in red and blue

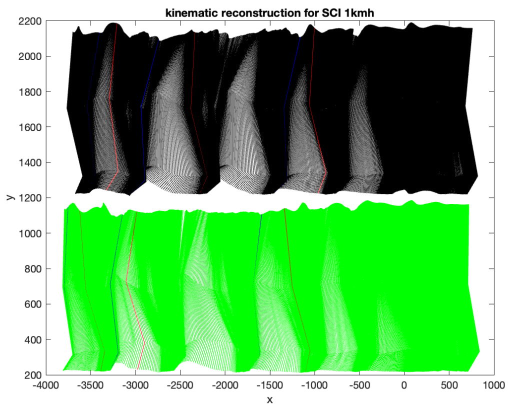


FIGURE 6
Foot off and strike event in SCI subject for both limb (right in green, left in black), marked in red and blue

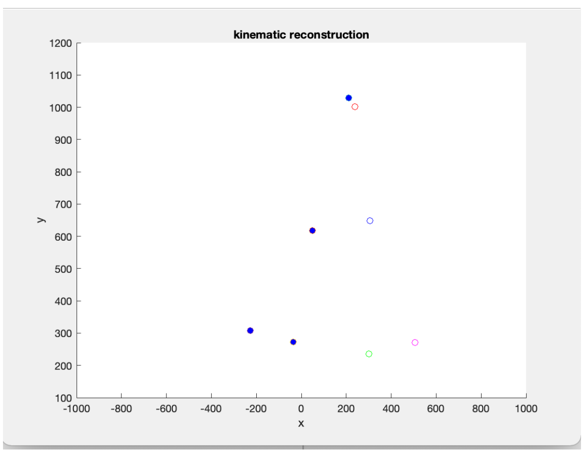


FIGURE 7
animation during a foot strike

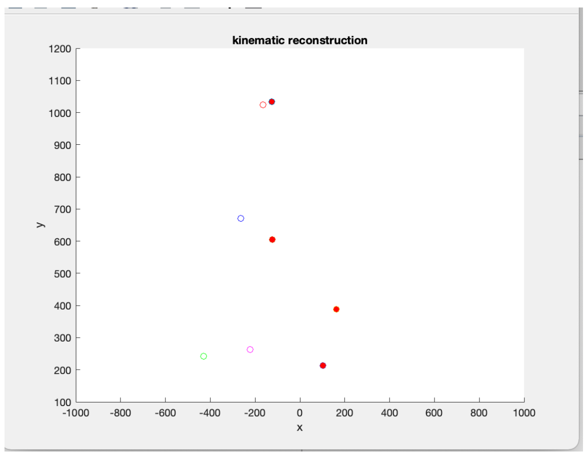


FIGURE 8
animation during a foot off

GAIT AND EMG PARAMETERS CHOICE

KINEMATIC PARAMETERS

We extracted kinematic parameters in order to perform the PCA. The chosen parameters are listed below:

Gait event parameters	
Gait time parameters	Cycle duration
	Swing duration left/right
	Double stance
	percentage of stance left/right
	Step height left/right
	Step length left/right
	Stride width
Stability parameters	Variability of vertical hip oscillation left/right
	Variability of lateral hip-midpoint oscillation
Joint angles and limb segment oscillations	Knee joint angle (minimal, maximal) left/right
Velocity	Knee joint angle velocity (maximal) left/right
Variability of gait	Variability of step height left/right
	Variability of step length left/right
	Variability of stride width
Total	25

The parameters choice is mainly based on the recorded videos that featured the spinal cord injured patients with and without electrical stimulation and comparing it to a healthy gait. We verified in the literature that they were indeed used, for instance in Courtine et al. 2009 [1]. In later steps we will exclude some parameters that shows high correlation. We defined the parameters as follows:

Cycle duration: the time between two consequent foot off of a limb, composed of a stance phase and a swing phase.
Swing duration : the time between the toe off and the following heel strike for a limb.
Percentage of stance left/right: proportion of the gait where the selected foot is on the ground.
double stance percentage: proportion of the gait where the two feet are on the ground. We choose to extract these parameters because the patient with spinal chord injury showed trouble executing the steps in the video, which changed the gait duration.
Step height:difference between the maximum value and the minimum value that was reached along the vertical axis by the ankle marker during a gait cycle. In this case, the difference between the healthy subject's and the patient's step height was also visible in the video. Indeed, the patient generally had trouble lifting his feet without stimulation, and can increase the height when stimulated.
Step length: distance traveled by a foot during the foot off and foot strike (adjusted regarding the speed of the treadmill).
Stride width: mean of the lateral distance between the two feet during a gate. we choose this parameter to translate a potential difference in the frontal/coronal plane (i.e the plane parallel to the foreheand and perpendicular to the sagittal plane)
Additionally, it could be beneficial to include parameters that capture variability. The observed videos indicate that healthy participants exhibited a consistent and smooth gait. For patients without stimulation, the steps are difficult and small. With stimulation, the variability of the movement increases. Variability was quantified by calculating the difference between an individual gait measurement and the average value across gait.
Variability of step height
variability of step length
Variability of stride width
Variability of vertical hip oscillation: was estimated as the standard deviation of the left and right hip along the vertical axis during a gait cycle.
Lateral variability of hip-midpoint: Deviation of the hip-midpoint along the lateral axis in a gate in comparison to the mean. Hip-midpoints represented the point in space located in the middle between the left and right hip markers.
Next, were extracted some parameters regarding joints. The knee joint angle could vary from a normal gait as the patient

has a toe-walking gait and is supported by multi-directional gravity assistance.

Maximum and minimum knee angles should be less extreme than in a healthy subject. The knee joint angle was calculated as the angle formed between two vectors that link the knee marker to the ankle marker and the knee marker to the hip marker.

Knee joint ankle velocity: differentiating the value of knee joint ankle. This parameter should also be useful to differentiate between the healthy subject and the patient because the patient appears to perform slower movements.

EMG PREPROCESSING

Before extracting the EMG parameters, the signals are preprocessed. For that, we proceed in the following steps:

1. Rectify the signal with absolute value
2. Extract the envelope from the signal using the peak method: spline interpolation over local maxima separated by at least n samples, with n=500 chosen comparatively to the size of the signal over a gate cycle and adjusted by testing.
3. A lowpass filter is applied to the envelope to reduce the oscillations. From the literature [2], the most useful and important frequency ranges are within the range from 50 to 150 Hz. After testing, 150Hz was confirmed as a good cutoff frequency for the filter. However, the lower frequencies <50Hz were conserved.
4. Finally, to have an even smoother envelope, we apply a moving average filter.

An example of this preprocessing is shown in Figure 9.

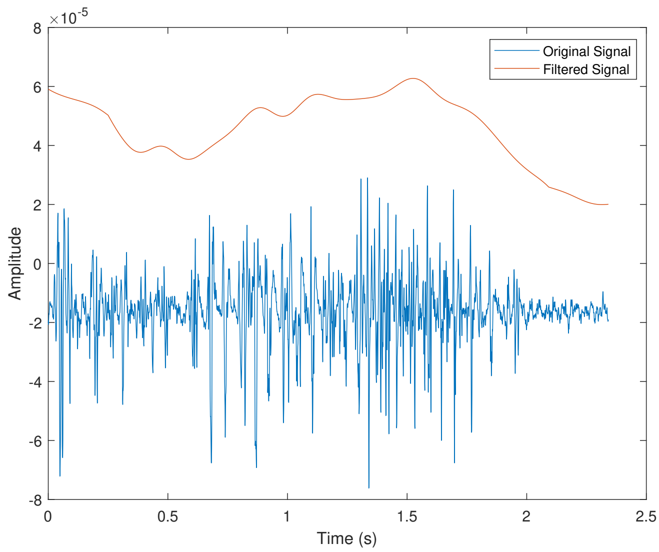


FIGURE 9
EMG signal preprocessing

EMG PARAMETERS

EMG parameters	Number of parameters
Left and right extensors mean amplitude (MG)	2
Left and right extensors and flexors Amplitude variation (SOL,MG,TA)	6
Left and right flexors and extensors burst duration (SOL,TA)	4
Left and right flexors and extensors burst duration variation (SOL,TA)	4
Flexor/Extensor Coactivation (SOL,TA)	1
Coactivation variation	1
Total	18

- The **extensor mean amplitudes** quantifies the level of muscle activation. Spinal cord injury causes perturbation on respective activation and thus should affect these parameters, especially with hyperreflexia, often affecting the subjects. The extensors and flexors **amplitude variation** similarly should highlight the differences in the muscles activation over the gait cycles. A healthy individual should have a regular contraction and thus present low variability while the SCI individuals should present higher variation from the difficulties they present, including because of faster fatigue.

- The **flexor/extensor coactivation** is characterized using the coactivation index. Different ways to compute it exist, and we chose the one defined by [3], integrated over the gait cycle and taken as a percentage:

$$CI = \frac{Signal_L(t)}{Signal_H(t)}(Signal_L(t) + Signal_H(t)) \quad (1)$$

  With $Signal_L$ the signal with the lowest amplitude and $Signal_H$ the highest. This index will quantify the relation between the flexor and extensor activities. We expect a certain level of coordination for healthy individuals that would be impacted for SCI subjects. We observed **coactivation variations** in the left and right leg CI for SCI subjects. Therefore, we chose to take the mean value between the legs, as well as the variance over gait cycles.

- The **burst duration** quantifies the duration of the muscle contraction, in our case over a gate cycle. For complementarity, we take it for both flexor and extensor. The behavior of the EMG envelope for the healthy individual is expected to describe a precise pattern repeated over the gait cycles with very few **burst duration variations**, while the SCI individual should highlight differences needed to maintain balance despite the dysfunction in muscle contraction. It could also vary more over time because of the quicker fatigue of the muscles. To compute the burst duration, we first detect the onset and its associated offset over the gait cycles, by setting 2 detection thresholds (low and high) over the signal amplitude. We then take the time difference between the onset and offset to be the burst duration. Note that in some cases we can have more than one onset/offset couple in a gait cycle. We just add the duration to get the total burst duration. An example of detection is depicted in Figure 10.

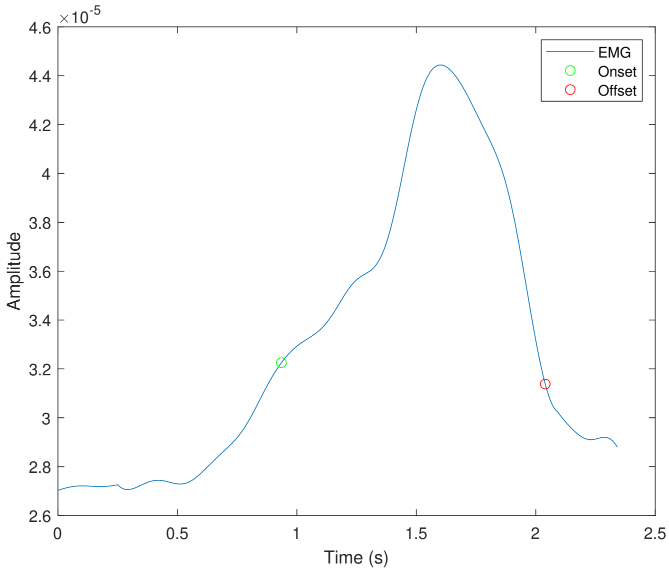
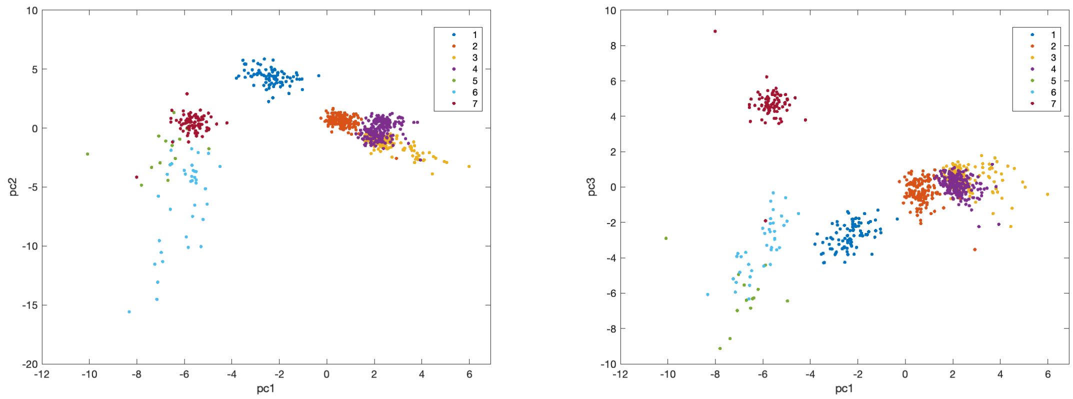


FIGURE 10
Onset/Offset detection for healthy medial gastrocnemius EMG

As flexor and extensor muscles couple, we chose Tibialis anterioris (as flexor) and Soleus (as extensor), providing information about plantar flexion and dorsiflexion. We also use Medial gastrocnemius for the amplitude.

PCA result and Discussion

A first PCA was thus created, after column normalization of the matrix of parameters (see fig. 11).
To better understand the underlying features, we also plotted the different parameters correlation in a matrix (see fig.12), explained variance of each pc (see fig. 13), and a biplot representing the weight/influence of each parameter for each pc in fig. 14. For a better overview, the three first principal components were always observed.
The three conditions of healthy, SCI with and without stimulation can be separated into relatively distinct clusters, and it is observed that the population of SCI with EES stimulation is significantly nearer to the healthy population than the SCI one without stimulation. This underlines the fact that EES stimulation is a potential way of restoring a better gait cycle.
The different speeds in healthy subjects are also quite clear and seem to mostly correlate with pc1. Pc3 seems to differentiate the best between SCI with and without EES stimulation. From fig. 13, it is observed that pc3 is sufficiently prominent, with a similarly explained variance to pc2. To better understand the effects of pc3, which seems to differentiate the best between SCI with and without EES stimulation (see biplot in fig. 14), the parameters contributing the most to pc3 were observed: double_stance_percentage, stance_percentage for right and left, and, negatively, stride_width.



(A) PC 1 and 2

(B) PC 1 and 3

Figure 11

PCA results with all parameters. 1-4 represent healthy individuals at different speeds/inclination: 1km/h, 2km/h, 3km/h, and 3km/h inclined respectively; 5-6 SCI individuals with EES at 1 and 2 km/h; 7 SCI individuals without EES

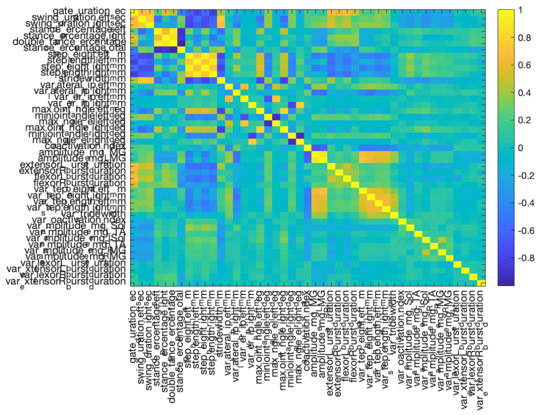


Figure 12
Correlation matrix of all parameters

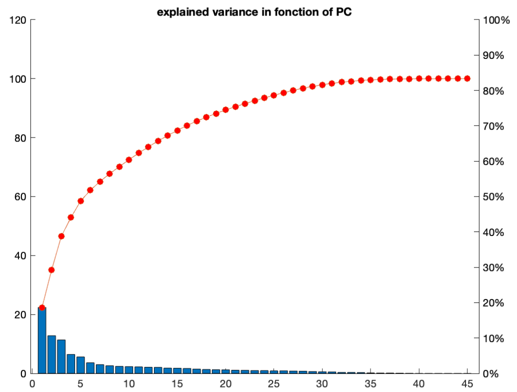
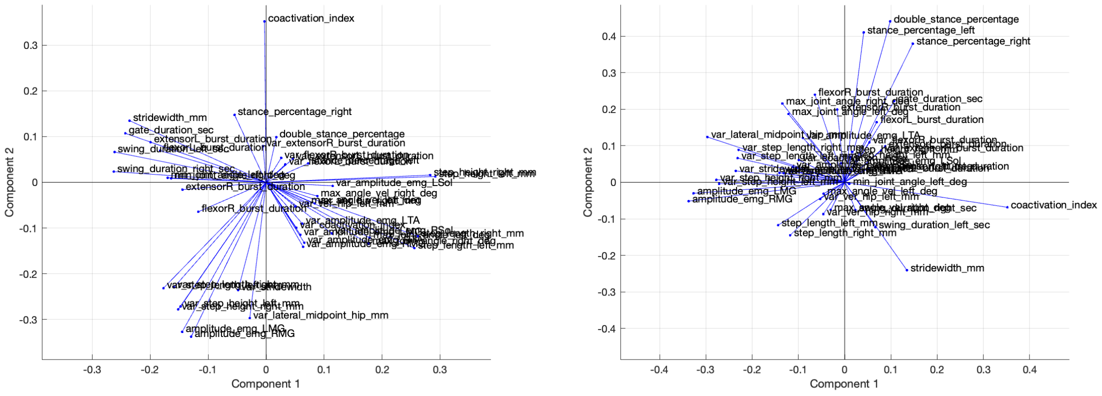


Figure 13
Biplot of all parameter with PC 1 and 2

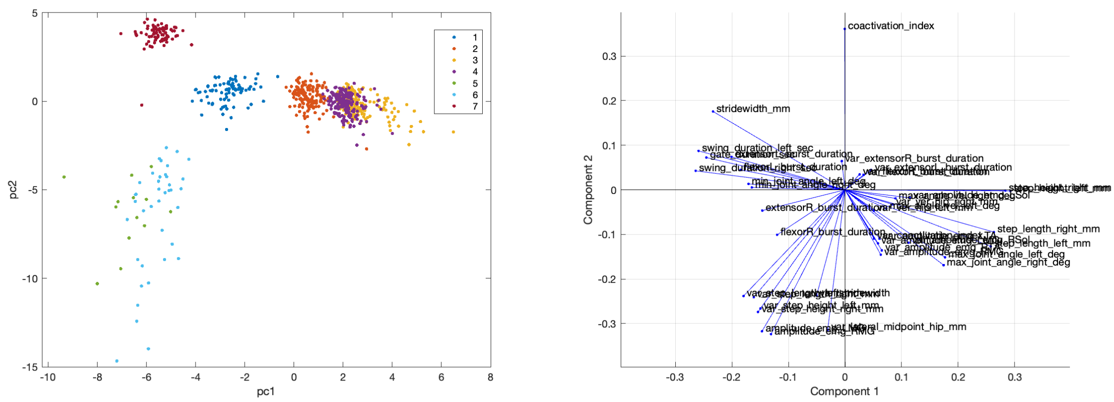


(A) PC 1 and PC 2

(B) PC 2 and 3

FIGURE 14
Biplot of all parameter

Based on fig 12, some parameters were thought as too dependent on other already existing parameters and were thus discarded: *stance_percentage* and everything related to stance, as it was correlated to swing and gate duration. Left or right leg discarding was also tried, as well as computing symmetry of parameter, but every trial "worsened" the resulting PCA. The resulting pca is presented in fig. 15.
This is understandable, as the parameters that helped the more the differentiation are the ones weighing the most in pc3, but are also the ones that are heavily correlated. It must thus be noted that these parameters, while being very helpful in our goal of distinguishing the different populations, are also overweighing the whole analysis in fig. 11. Nevertheless, clusters of the different populations are still very visible, and EES clearly differentiated from the SCI group.

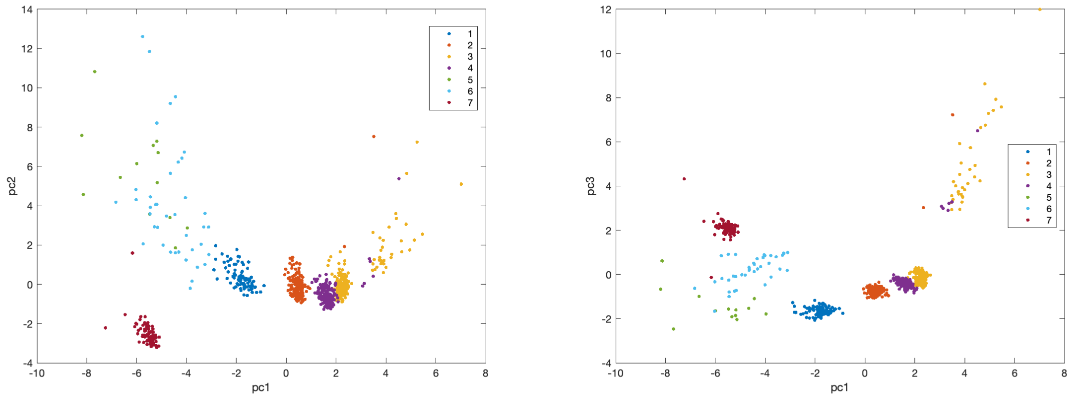


(A) PC 1 and 2

(B) Biplot for PC 1 and 2

FIGURE 15
PCA results after discarding heavily correlated features. 1-4 healthy at different speeds: 1km/h, 2km/h, 3km/h, and 3km/h inclined respectively; 5-6 SCI with EES at 1 and 2 km/h; 7 SCI without EES

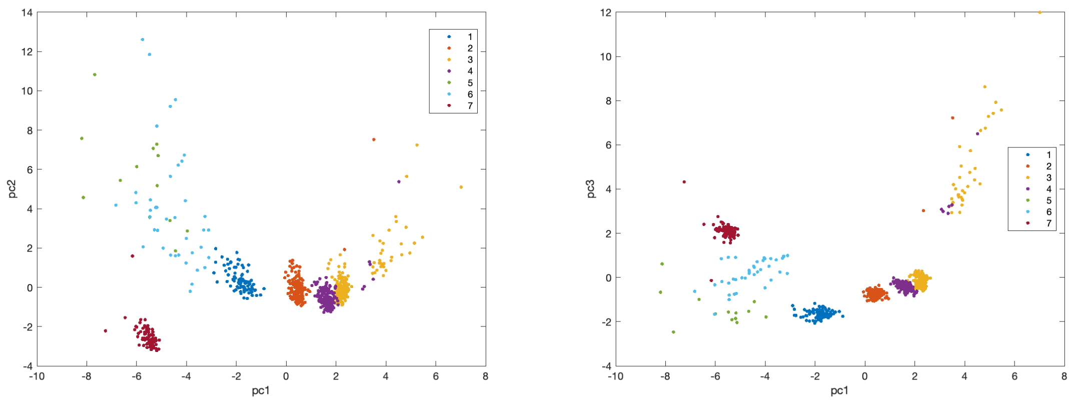
After analysis of the biplots in fig. 15, it has been observed that the parameters dragging the EES stimulated away from the healthy were the var_length and height parameters. So another PCA was tried without the presence of these parameters in fig. 16, that shows much better results than in fig. 15: the SCI with EES are much nearer to the healthy gait cycles.
This would lead to the understanding that while working well, EES must still be optimized as it induces a much more variable gait pattern than healthy gait. Similar results can be found when removing EMG amplitude, another hint that EES does not yet achieve a natural activation of muscle pattern.



(A) PC 1 and 2 (B) PC 1 and 3

FIGURE 16
PCA results after discarding heavily correlated features. 1-4 healthy at different speeds: 1km/h, 2km/h, 3km/h, and 3km/h inclined respectively; 5-6 SCI with EES at 1 and 2 km/h; 7 SCI without EES

Another PCA was performed, without EMG parameters, in order to analyze their impact on the analysis (see fig. 17). The distinction between all the different subject populations is still possible, and the same trends of SCI with stimulation being nearer to healthy population than SCI without stimulation are visible. Nevertheless, pc2 now plays a greater role, which is perhaps an indication that the distinguishing factor of late pc3 in fig. 11 was heavily influenced by muscle activation or that late pc2 was influenced by them and led to a worsening of the results. In the later case, it would indicate that muscle activation plays no great role in the EES system, which is not very probable. But it can be said that only having kinematic markers is already enough to differentiate the different populations.



(A) PC 1 and 2 (B) PC 1 and 3

FIGURE 17
PCA results with kinematic parameters only. 1-4 healthy at different speeds: 1km/h, 2km/h, 3km/h, and 3km/h inclined respectively; 5-6 SCI with EES at 1 and 2 km/h; 7 SCI without EES

Overall, group segregation was achieved, with trends permitting to observe that EES stimulation would reinforce healthy gait in SCI patients.
By analyzing the different parameters that influence the most certain PCs, it is possible to see how this stimulation could be restoring gait and what must be optimized to achieve more natural gaits.
With stimulation, the ability to perform high and long step is improved. The movement is easier, the speed increases. Stance percentage and related parameters seem to be greatly improved by EES stimulation.
However, the variability of gait is still a big problem.
Without stimulation, the activation of the muscle is very light (incomplete injury). In healthy patient, the activation of the muscle is optimised to perform regular and efficient movement while minimizing fatigue. The EES tries to improve theses activations and abilities, but is not as optimised as healthy behaviour.

Bibliography

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[3] K.S. Rudolph, M.J. Axe, and L. Snyder-Mackler. Dynamic stability after acl injury: Who can hop? *Knee Surgery, Sports Traumatology, Arthroscopy*, 8(5):262–269, 2000.