# Predictive Gait Quality Measures Using Modular Neuromuscular Control Parameters in Chronic Post-stroke Individuals

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## Abstract

**Background:** Recent evidence suggests that disinhibition and/or hyperexcitation of the brainstem descending pathways and intraspinal motor network diffuse spastic synergistic activation patterns after stroke. This results in simplified or merged muscle sets (i.e., muscle modules or synergies) compared to non-impaired individuals and this leads to poor walking performance. However, the causal relations of how these neuromuscular deficits influence gait quality (e.g., symmetry or natural walking patterns) are still unclear. The objective of this exploratory study was to investigate the relations of modular neuromuscular framework and gait quality measures in chronic stroke individuals.

**Methods:** Sixteen chronic post-stroke individuals participated in this study. Full lower body three-dimensional kinematics and electromyography (EMG) were concurrently measured during overground walking at a comfortable speed. We classified subjects into two groups based on the number of muscle modules and compared gait quality measures using a two-sampled t-test. Then, a stepwise multiple regression was used to investigate the optimal combination of the neuromuscular parameters to predict gait quality measures.

**Results:** Subjects who had a reduced number of muscle modules had greater asymmetry in the kinematic parameters including limb length ($p<0.01$), footpath area ($p<0.01$), hip ($p<0.05$) and knee ($p<0.01$) flexion/extensions, and hip abduction/adduction ($p<0.01$). We also found that the gait quality measures were predictable with the input variables from the modular neuromuscular control framework including variability accounted for ($VAF$) information from the muscle modules and area under the EMG envelope curves of the quadriceps (i.e., rectus femoris and vastus lateralis) and tibialis anterior muscles with significant association (average $R^2 = 45.6\%$).

**Conclusions:** The results suggest that there exists a strong correlation between the neuromuscular control framework and the gait quality measures. This study helps to understand the underlying causality of disturbances in gait quality and provides insight for a more comprehensive outcome measure to assess gait impairment after stroke.

**Key words**: muscle module, muscle synergy, gait quality, gait symmetry, stroke

## Background

Effective gait recovery after a stroke involves improvements both in functional mobility and quality of movement. Most of the clinical outcomes in gait studies have focused on functional indices that provide a holistic picture of walking performance and recovery [1], [2]. On the other hand, an increased number of recent studies accentuate the importance of monitoring detailed gait quality to assess gait impairments [3]. Disturbances in gait quality are associated with an increased risk of falls [4], greater energy expenditure [5], and long-term problems such as learned non-use or use-dependent plasticity, musculoskeletal injuries, and pain [6], [7].

Symmetry is a common measure to characterize disturbances in gait quality. While spatiotemporal symmetry (e.g., step length, step time) has been well charted to describe walking [8], post-stroke individuals exhibit significant asymmetry in joint kinematics with greater inter-individual variability than spatiotemporal measures [9]. Typical asymmetry in joint kinematics includes reduced hip extension, knee flexion and ankle dorsi/plantarflexion, and knee hyperextension on the impaired side [10]. Limb kinematics, related to the end-effector (i.e., foot) motion in task space, has also been indicated as an important parameter for locomotor function [3]. For instance, Shin et al., found that post-stroke individuals preferentially coordinated the paretic side of limb function using limb kinematics by compensating joint kinematics during walking [3].

Neuromuscular activity is crucial to execute biomechanical functions such as gait [11]. Previous studies have shown that muscle activity during walking can be grouped into sets of co-excited muscles (also known as muscle modules or synergies) [12]. These modules may originate from neural-adaptations caused by repetitive activities and may reduce the computational cost in selecting strategies of motor coordination [13]. Previous studies have identified that well-coordinated gait in healthy individuals can be produced by four group of modules [12]. Other studies suggest that the concept of muscle modules can be used as an outcome measure to assess motor recovery following therapeutic interventions [14].

Recent evidence suggests that disinhibition and/or hyperexcitation of the brainstem descending pathways and intraspinal motor network diffuse spastic synergistic activation post-stroke [15]. As a result, simplified or merged muscle sets compared to non-impaired individuals are typically observed and lead to poor walking performance, for instance, reduced walking speed with greater spatiotemporal asymmetry than those of healthy individuals [12]. While this study discusses somewhat the influence of neuromuscular deficit on gait impairment, no evidence exists to show how detailed gait quality measures are influenced by neuromuscular deficits. Thus, exploring relations between gait quality measures and neuromuscular deficits, such as merged muscle modules, may help to explain the underlying causality among impairments and locomotor functions after stroke.

The objective of this exploratory study was to investigate the relations of modular neuromuscular deficits and disturbances in gait quality measures (i.e., asymmetry) in terms of spatiotemporal, limb and joint kinematic parameters in chronic post-stroke individuals (see Fig. 1). We measured lower body electromyography (EMG) activities and gait kinematics concurrently during walking from 16 participants. We hypothesized that the post-stroke group with a reduced number of muscle modules will exhibit greater asymmetry in gait quality measures due to the loss of independence in motor activations [12]. Accordingly, we also expected to predict the gait quality measures with the input modular neuromuscular control framework assuming a causal relationship exists in these measures [16].

## Methods

### Participants

We recruited 16 individuals (6 left hemiparesis, 12 male, age: 62.9$\pm$11.1 years) with chronic stroke (> 6 months) to participate in this study approved by the Institutional Review Board of Korea Advanced Institute of Science and Technology. Individuals ranged in age and impairment level (see Table 1). The inclusion criteria were as follows: at least 6 months after stroke, independent walking without falling regardless of walking speed, and over 70 points of Modified Barthel index. The exclusion criteria were as follows: perceptual and cognitive dysfunction and over 3 points on the Modified Ashworth Scale. Prior to the experiment, the experimenter explained all the experimental procedures to each participant and obtained informed consent.

### Experimental Setup and Data Collection

Full lower body three-dimensional kinematics and EMG data were collected concurrently during overground walking from each participant. Gait kinematics were acquired using the VICON Motion Capture System (MX T-series Vicon Motion Systems Ltd, Oxford, UK), consisting of eight cameras at 100Hz. Surface EMG data were amplified and measured at 2000Hz with Delsys Trigno (Delsys, Inc., Natick, MA) from 16 bilateral electrodes placed on the muscles including extensor halluces longus ($EHL$), tibialis anterior ($TA$), soleus ($SO$), gastrocnemius ($GA$), vastus lateralis ($VA$), rectus femoris ($RF$), semitendinosus ($SM$), and biceps femoris ($BF$).

Each participant completed 4-6 trials of walking back and forth on a plain six meters walkway at a comfortable speed. Participants did not use any of assistive devices such as a cane, walker or ankle foot orthosis (AFO) during the recording sessions. All participants wore a harness without any body weight support for safety to catch them if needed to prevent possible falls.

## Kinematic Data Analysis

Visual 3D v6 Professional (C-Motion, Inc., Germantown, MD) software was used to extract three-axis joint angle trajectories at pelvis and bilateral hip, knee and ankle from the marker data for each trial. Custom software was written in MATLAB (Mathworks, Inc. R2016a, Natick, MA) to calculate features and outcomes. The joint angle trajectories and EMG data were truncated and normalized into 100% of the gait cycle from heel strike to heel strike events for each trial [17]. An example of the recorded gait kinematics data of bilateral joint angle trajectories of a single gait cycle in the sagittal plane is illustrated in Fig. 2.

## Modular Neuromuscular Control Parameters

### Area under the EMG envelope

The selected EMG signals from each participant were high-pass filtered at 40Hz with a zero-lag fourth-order Butterworth filter, demeaned, rectified, and low-pass filtered with a zero-lag fourth-order Butterworth filter at 10Hz, resulting in the EMG envelope [18]. For each muscle, the filtered signal was normalized to its peak value then the area under the EMG envelope curve was calculated and used to represent the neuromuscular indicator as $A_{i,j}$ where $i$ can be $EHL$, $TA$, $SO$, $GA$, $VA$, $RF$, $SM$, or $BF$, and $j$ can be the unaffected ($US$) or affected ($AS$) side. An example area under the EMG envelope curve at $TA$ of a participant (P1) is depicted in Fig. 3.

### Muscle Modules

The processed EMG signals were decomposed into muscle group weightings and activation timing patterns using nonnegative matrix factorization (NNMF) as previously described in [12]. The NNMF determined the minimum number of muscle modules based on a reconstruction quality criterion: variability accounted for ($VAF$) ≥ 90% [12]. We additionally executed the NNMF algorithm five times, considering that one to five modules were needed for the EMG reconstruction. In this work, the parameters to represent the muscle modules included: number of muscle modules at each side ($MM_{US}$ and $MM_{AS}$), total number of muscle modules at both sides (i.e., $MM_{Total} = MM_{US} + MM_{AS}$), value at $VAF \geq 90\%$ ($VAF_{US}$ and $VAF_{AS}$), and $VAF$ values with one to five modules ($VAF_{US,k}$ and $VAF_{AS,k}$, where $k = 1, \cdots, 5$).

**Gait Performance Measure**

**Gait Quality Measures**

We categorized the gait quality measures into spatiotemporal, limb, and joint kinematic domains [3]. The parameters were extracted by imposing the average joint kinematics data of a single gait cycle into a lower body model. Spatiotemporal parameters included step length ($SL$) and step time ($ST$), defined as the linear distance between right and left feet, and the duration of each step, respectively. The parameters of limb kinematics incorporate leg extension angle ($LEA$) [19], limb length ($LL$) [20], and footpath area ($FPA$) [21] defined as the angle between a line from hip to the foot and vertical before toe-off, the range of linear distance between hip and the foot, and the area under the foot pattern from hip sagittal plain during gait cycle, respectively. The parameters of joint kinematics were defined as the range of motion (RoM) of selected joints including all rotations of hip, knee flex/extension, and ankle dorsi/plantarflexion.

The symmetry index metric [22] was used to evaluate the gait quality given by

$$SI_n = \frac{US_n - AS_n}{0.5(US_n + AS_n)} \quad (1)$$

where $US_n$ and $AS_n$ are the $n^{th}$ gait parameter of the unaffected and affected sides, respectively, and $n$ can be the aforementioned spatiotemporal, limb and joint kinematic parameters. The value is always between -2 to 2, and a positive (or negative) value indicates $US > AS$ (or vice versa) [22]. Note that the symmetry index, $SI_n = 0$, when perfect symmetry.

**Functional Gait Measure**

For the functional gait measure, we selected gait speed ($GS$) because speed is a well-accepted indicator of gait performance after stroke [23].

**Statistical Analysis**

Subjects were classified into two groups based on the criterion of total number of muscle modules at both sides equal or less than four (i.e., $MM_{Total} \leq 4$), which was determined by rounding the average total number of muscle modules ($MM_{Average} = 4.37$) of all subjects. A two-sided, two-sample t-test was used to test the difference of gait performance measures between the two groups with a significance level of $\alpha < 0.05$.

Second, a stepwise multiple regression analysis was used to investigate which combination of the neuromuscular parameters was best associated with gait quality measures with a significance level of $\alpha < 0.05$. A total of 32 aforementioned independent variables including the modular neuromuscular control parameters and a functional gait measure (i.e., speed) were selected. The dependent variables were the gait quality measures including symmetry index of spatiotemporal, limb and joint kinematic parameters. A preliminary analysis was conducted using a linear regression on each considered independent variable and each dependent variable to minimize the number of independent variables and to simplify the final model as possible. Only those independent variable candidates with $p$-value $\leq 0.05$ were selected as input for the stepwise multiple regression analysis.

## Results

### Classification based on Number of Muscle Modules

The average total number of modules ($MM_{Total}$) was 4.37 with a minimum and maximum of two and six modules, respectively. We classified subjects whose total number of muscle modules were equal or less than four (i.e., $MM_{Total} \leq 4$) into Group 1 and the rest of the subjects (i.e., $MM_{Total} > 4$) into Group 2. A total seven of subjects were classified into Group 1 (subject ID: 3, 4, 5, 6, 8, 10, and 13), and nine subjects were included into Group 2 (subject ID: 1, 2, 7, 9, 11, 12, 14, 15, and 16). All results are summarized in Table 2.

A two-sided, two-sample t-test was used to evaluate the significant difference of each gait parameter (i.e., symmetry index) between the two groups. Among all the gait parameters, symmetry indices of $LL$ ($p$<0.01) and $FPA$ ($p$<0.01) from limb kinematics and hip flex/extension ($p$<0.05), hip abd/adduction ($p$<0.01), and knee flex/extension ($p$<0.01) from joint kinematics revealed a significant difference between the two groups. While gait speed ($p$=0.07) and ankle dorsi/plantarflexion ($p$=0.06) revealed a considerably strong difference, these parameters including other parameters did not reveal a significant difference between the two groups (see Table 3).

We additionally fitted a linear regression model on the symmetry index of those significant parameters including $LL$ ($p$<0.05), $FPA$ ($p$<0.05), hip flex/extension ($p$=0.10), hip abd/adduction ($p$<0.05), and knee flex/extension ($p$<0.05) across the total number of modules. All parameters except for hip flex/extension still revealed a significant trend in the slope of the linear regression models (See Fig. 4).

## Stepwise Regression to Predict Gait Features

### Prediction of Spatiotemporal Parameters

For $SL$, the stepwise regression analysis selected $VAF_{AS}$ ($\beta_1 = -10.29$) and $A_{RF,AS}$ ($\beta_2 = 14.01$) as independent variables. The model revealed a statistically significant relationship ($F = 8.26$, $p < 0.001$) and accounted for approximately 56% of the variance of $SL$ ($R^2 = 0.56$, $Adjusted\ R^2 = 0.49$). In contrast, none of the independent variable candidates had a $p$-value $< 0.05$ for $ST$ (see Table 4). The visualization of the regression model with selected independent variables is shown in Fig. 5 (top left).

### Prediction of Limb Kinematic Parameters

For $LEA$, the stepwise regression analysis selected $A_{RF,AS}$ ($\beta_1 = 15.18$) as an independent variable, was statistically significant ($F = 9.16$, $p < 0.001$), and accounted for approximately 40% of the variance ($R^2 = 0.40$, $Adjusted\ R^2 = 0.35$). For $LL$ and $FPA$, both stepwise regression analyses selected $VAF_{AS,3}$ ($\beta_1 = 17.82$ for $LL$ and $\beta_1 = 20.52$ for $FPA$) as an independent variable. The fitted models were statistically significant ($F = 5.96$, $p < 0.05$ for $LL$ and $F = 7.73$, $p < 0.05$ for $FPA$) and accounted for approximately 30% and 36% of the variance of $LL$ and $FPA$, respectively ($R^2 = 0.30$, $Adjusted\ R^2 = 0.25$ for $LL$ and $R^2 = 0.36$, $Adjusted\ R^2 = 0.31$ for $FPA$). The results are summarized in Table 4 with the visualization of the regression models with selected independent variables shown in Fig. 5 (top right three).

### Prediction of Joint Kinematic Parameters

For the hip flex/extension, the stepwise regression analysis selected $VAF_{US,1}$ ($\beta_1 = 2.27$) and $A_{RF,US}$ ($\beta_2 = 4.91$) as the independent variables and were statistically significant ($F = 13.0$, $p < 0.001$) accounting for approximately 67% of the variance ($R^2 = 0.67$, $Adjusted\ R^2 = 0.62$). For the hip abd/adduction, the stepwise regression analysis selected $VAF_{US,1}$ ($\beta_1 = 2.56$) and $A_{VL,AS}$ ($\beta_2 = 1.76$) as the independent variables and were statistically significant ($F = 8.39$, $p < 0.01$) accounting for approximately 56% of the variance ($R^2 = 0.56$, $Adjusted\ R^2 = 0.50$). For the hip int/external rotation, the stepwise regression analysis selected $A_{TA,US}$ ($\beta_1 = -2.25$) as the independent variable and was statistically significant ($F = 8.39$, $p < 0.01$) accounting for approximately 39% of the variance ($R^2 = 0.39$, $Adjusted\ R^2 = 0.35$). For the knee flex/extension, the stepwise regression analysis selected $VAF_{AS,3}$ ($\beta_1 = 19.24$) as the independent variable. The fitted model was statistically significant ($F = 9.91$, $p < 0.01$) and accounted for approximately 41% of the variance of the knee flex/extension ($R^2 = 0.41$, $Adjusted\ R^2 = 0.37$). Finally, for the ankle dorsi/plantarflexion, none of the independent variable candidates had a $p$-value $< 0.05$. (See Table 4). The visualization of the regression models with selected independent variables is shown in Fig. 5 (bottom row).

## Discussion

The major goal of this study was to delineate the causal relations of modular neuromuscular control parameters and quality of movement during gait after stroke. The main findings were as follows: first, post-stroke individuals with a reduced number of muscle modules exhibit greater asymmetry in gait quality measures, particularly in kinematics level. Second, the gait quality measures were predictable with modular neuromuscular control parameters extracted from the EMG data. Specifically, those parameters were variability accounted for ($VAF$) information from muscle modules (i.e., $VAF_{AS}$, $VAF_{AS,3}$, and $VAF_{US,1}$) and area under the EMG envelope curves from rectus femoris, vastus lateralis, and tibialis anterior muscles (i.e., $A_{RF,AS}$, $A_{RF,US}$, $A_{VL,AS}$, and $A_{TA,US}$). To our knowledge, this work is a novel in the fact that it integrates detailed gait quality measures with the neuromuscular control framework. The results in this study offer preliminary evidence justifying that the modular neuromuscular framework can be a useful predictor of gait quality measures and help to understand the underlying causality of disturbances in gait quality after stroke.

The analysis of the muscle modules has become a more popular tool to describe the neuromotor control of multi-limb movement such as gait after stroke [12]. For the analysis, many previous studies classified muscle modules into paretic and non-paretic sides [12], [24], [25]. While this is a reasonable separation given that most stroke populations exhibit a hemiplegic gait, our rationale was that walking is essentially the performance of an inter-coordinated behavior between both legs. Thus, we analyzed the data from a different perspective of classifying participant groups based on the total number of muscle modules of both sides. Our data revealed that there is a significant difference in gait quality measures between the groups, indicating a link between the total number of modules and the gait quality. This result is consistent with a previous study that found merged muscle module is critical to poor walking performance [25]. This also justifies the investigation of therapeutic interventions that can increase the number of modules to improve the gait quality after stroke [14].

One thing to note is that most participants in our data had a relatively severe gait impairment with slow walking speed (average speed: 0.29$\pm$0.13 m/s, see Table 1) [26]. Nevertheless, we found significant differences in gait quality measures between the groups and those differences were mostly observed in the kinematic parameters (see Table 3). However, none of the parameters from spatiotemporal characteristics and functional gait measure (i.e., speed) revealed a significant difference between the groups. These results correspond with previous research that found post-stroke individuals exhibit significant asymmetry in joint kinematics with greater inter-individual variability than spatiotemporal characteristics [9]. Given that significance was observed between the groups within a severe population in our data, we speculate to find a more distinct trend with a larger sample size with various severity levels including mild to moderately impaired stroke population.

A recent study attempted to combine parameters from muscle modules and gait analysis (i.e., spatiotemporal and joint kinematics) to predict functional outcomes such as walking speed [24]. While this study successfully predicted locomotor function with combined biomechanical and neuromuscular measures, the relations between those measures, which would more likely to have direct causal relations, were not analyzed. Thus, we used the stepwise multiple regression approach to find the optimal linear regression model that predicts the gait quality measures with the input modular neuromuscular control parameters. We found that all symmetry indices of gait quality measures, except for step time and ankle dorsi/plantarflexion, were predictable with the neuromuscular modular control parameters with significant associations (see Table 4). Common predictors included quadriceps muscles (i.e., rectus femoris and vastus lateralis) and information from variability accounted for ($VAF$) in the regression models. The inclusion of quadriceps were expected as these muscles have long been believed to be key contributors to hip and knee motion during gait [27]. $VAF$s were also commonly selected because these parameters are critical information determining the number of muscle modules [24]. On the other hand, it is unclear why the tibialis anterior muscle appeared to be negatively associated with hip internal/external rotation given that this muscle is known as ankle dorsiflexor. This result may be related to abnormal compensatory coupling between irrelevant muscles due to neurological impairment [28]. However, further research is needed where the EMG measures at other locations such as hip lateral rotator group muscles are added to investigate this connection, which may indeed be epiphenomenal. Overall, these results suggest causal relations exist between the neuromuscular control framework and the gait quality measures.

One possible therapeutic application of this causal relationship would be using the concept of neuromuscular and gait quality parameters as outcome measures to assess gait impairment after stroke. An example of previous research would be a locomotor intervention study that applied muscle modules as pre- and post-therapy outcome measures [14], [29]. These studies found increase in number of muscle modules and improvements in quality of modular organization (i.e., timing and compositions) as well as clinical measures such as gait speed after a locomotor rehabilitation therapy. This indicates that therapeutic interventions can change or improve the neuromuscular control framework, but the influence of these interventions on detailed movement quality was not reported in these studies. Thus, we expect the application of the neuromuscular and gait quality parameters as outcome measures will fill the gap and provide a more comprehensive characterization of gait recovery post-stroke.

The purpose of this proof-of-concept study was to provide initial evidence of causal relations between gait quality and neuromuscular parameters for chronic post-stroke individuals. However, this study was limited to a small sample size of 16 patients with a restricted range of impairment level; only severely impaired individuals with a slow walking speed participated in this work. However, our data still showed clear initial results on the relative importance of several predictors, providing the significant causal relationships exist between neuromuscular control framework and gait quality measures. We expect this methodology can be potentially used for gait training research or in clinical practice to understand impairments related to gait function.

## Conclusions

The purpose of this study was to investigate the influence of modular neuromuscular control framework on gait quality measures. We observed that chronic post-stroke individuals with a reduced number of muscle modules exhibit a greater deficit in gait quality measures, particularly in kinematics level. We also found that the gait quality measures are predictive with the input modular neuromuscular control variables. We conclude that there exists causal relations between the neuromuscular control framework and gait quality measures. These promising results justify further research with a larger post-stroke population and expanded range of impairment level for more reliable generalization.

## List of abbreviations

AFO: ankle foot orthosis; $AS$: affected side; $BF$: biceps femoris; $EHL$: extensor halluces longus; EMG: electromyography; $FPA$: footpath area; $GA$: gastrocnemius; $GS$: gait speed; $LEA$: leg extension angle; $LL$: limb length; $MM$: muscle module; NNMF: nonnegative matrix factorization; $RF$: rectus femoris; RoM: range of motion; $SI$: symmetry index; $SL$: step length; $SM$: semitendinosus; $SO$: soleus; $ST$: step time; $TA$: tibialis anterior; $US$: unaffected side; $VA$: vastus lateralis; $VAF$: variability accounted for

## Ethics approval and consent to participate

This study was approved by Institutional Review Board of the Korea Advanced Institute of Science and Technology (KH2019-05). All subjects gave written informed consent prior to data collection.

**Consent for publication**

Participants gave written informed consent to data treatment in this research study and permission to publish anonymous data and results.

**Availability of data and materials**

The data collected in this study are available from the corresponding author on reasonable request.

**Competing interests**

The authors declare that they have no competing interests.

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**Author's contribution**

SYS drafted the complete manuscript, performed data post-processing and statistical data analysis. YK participated in conducting experimental data collection, recruited subjects and managed IRB approvals. AJ and HSP conceived the whole idea, managed IRB approvals and helped in finalizing the manuscript. All authors read and approved the final manuscript.

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## Figure Legends

**Figure 1.** Overview of the study.

**Figure 2.** Example joint angle trajectories of a single gait cycle (heel strike to heel strike) in sagittal plane, hip flexion/extension (left), knee flexion/extension (middle), and ankle dorsi/plantarflexion (right).

**Figure 3.** Example area under the EMG envelope curve of tibialis anterior muscle from participant P1. A.U. in the y-axis indicates arbitrary unit.

**Figure 4.** Symmetry index ($SI$) of significant gait parameters including limb length ($LL$), footpath area ($FPA$), hip flex/extension ($Hip\ FE$), hip abd/adduction ($Hip\ AA$) and knee flex/extension ($Knee\ FE$) with increased total number of muscle modules at both sides ($MM_{Total}$). Linear regression models (bottom, right) were fitted on each gait parameter. The shaded area indicates 95% confidence interval.

**Figure 5.** Regression models with selected independent variables (see Table 3) from stepwise multiple regression. Note that a plane in three-dimensional space is illustrated with two independent variables for step length, hip flex/extension and hip abd/adduction.

**Table 1.** Demographics and clinical characteristics of the participants.

| ID | Age (years) | Sex | Height (cm) | Weight (kg) | Side affected | Time after stroke (years) | Type of lesion | FMA | FIM | Speed (m/s) |
|---|---|---|---|---|---|---|---|---|---|---|
| P1 | 59 | M | 170 | 69 | R | 4 | Ischemic | 21 | 11 | 0.29 |
| P2 | 61 | M | 169 | 72 | L | 3 | Ischemic | 16 | 9 | 0.27 |
| P3 | 70 | M | 158 | 69 | R | 2 | Ischemic | 12 | 12 | 0.16 |
| P4 | 55 | F | 158 | 60 | L | 11 | Hemorrhage | 22 | 14 | 0.24 |
| P5 | 59 | M | 176.5 | 66 | R | 3 | Ischemic | 13 | 8 | 0.21 |
| P6 | 73 | M | 170 | 74 | Both | 21 | Hemorrhage | 22 | 3 | 0.18 |
| P7 | 75 | F | 153 | 49 | R | 5 | Ischemic | 25 | 12 | 0.20 |
| P8 | 75 | M | 164 | 62 | R | 15 | Ischemic | 18 | 13 | 0.31 |
| P9 | 68 | M | 172 | 83 | L | 10 | Ischemic | 26 | 13 | 0.46 |
| P10 | 36 | M | 173 | 80 | L | 1 | Ischemic | 17 | 7 | 0.15 |
| P11 | 77 | M | 169 | 58 | R | 25 | Ischemic | 10 | 12 | 0.26 |
| P12 | 55 | M | 177 | 84 | L | 13 | Ischemic | 15 | 14 | 0.37 |
| P13 | 47 | F | 163 | 57 | R | 4 | Hemorrhage | 19 | 13 | 0.29 |
| P14 | 64 | M | 172 | 81 | R | 27 | Ischemic | 31 | 14 | 0.49 |
| P15 | 62 | F | 156 | 57 | L | 15 | Hemorrhage | 16 | 11 | 0.13 |
| P16 | 70 | M | 171 | 83 | R | 18 | Ischemic | 27 | 12 | 0.58 |

M – male, F – female, R – right, L – left, FMA – Fugl-Meyer assessment (max: 34), FIM – Functional Independent Measure (locomotion, max: 14)

**Table 2**. Classification of the subject groups based on the total number of muscle modules at both sides

| Group | $MM_{Total}$ | $MM_{US}$ | $MM_{AS}$ | Subject ID | Number of Subjects |
|---|---|---|---|---|---|
| Group 1 | 2 | 1 | 1 | P6 | 1 |
| | 3 | 2 | 1 | P4, P10 | 2 |
| | 4 | 2 | 2 | P3, P5, P8, P13 | 4 |
| Group 2 | 5 | 2 | 3 | P7 | 1 |
| | 5 | 3 | 2 | P1, P2, P9, P11, P12, P14, P15 | 7 |
| | 6 | 3 | 3 | P16 | 1 |

$MM$ – number of muscle modules, $US$ – unaffected side, $AS$ – affected side

**Table 3.** Results of the two-sided, two-sample t-tests of gait performance measures between two groups

| Gait Features | SI Parameters [%] | Group1 | Group2 | 95% CI | p-value |
|---|---|---|---|---|---|
| Functional | Speed | 0.22±0.06 | 0.34±0.15 | [-0.25, 0.01] | 0.07 |
| Spatiotemporal characteristics | Step length | -0.34±0.34 | -0.44±0.32 | [-0.27, 0.45] | 0.59 |
| | Step duration | -0.19±0.15 | -0.15±0.08 | [-0.16, 0.09] | 0.58 |
| Limb kinematics | Leg extension angle | -0.05±0.27 | -0.16±0.35 | [-0.23, 0.45] | 0.50 |
| | Limb length | 0.84±0.10 | 0.38±0.35 | [0.17, 0.76] | < 0.01 |
| | Footpath area | 1.04±0.13 | 0.51±0.36 | [0.22, 0.84] | < 0.01 |
| Joint kinematics | Hip flex/ex | 0.67±0.27 | 0.38±0.18 | [0.04, 0.53] | < 0.05 |
| | Hip abd/add | 0.31±0.25 | -0.02±0.16 | [0.11, 0.55] | < 0.01 |
| | Hip int/ext ro. | -0.05±0.14 | -0.02±0.23 | [-0.25, 0.18] | 0.75 |
| | Knee flex/ex | 0.56±0.23 | 0.15±0.23 | [0.15, 0.65] | < 0.01 |
| | Ankle dorsi/plantar | 0.37±0.36 | 0.05±0.25 | [-0.01, 0.64] | 0.06 |

SI – symmetry index, flex/ex – flexion/extension, abd/add – abduction/adduction, int/ext ro. – internal/external rotation, dorsi/plantar – dorsi/plantarflexion, CI – confidence interval

**Table 4.** Results of the stepwise multiple regression models with the dependent variable of symmetry ratio of gait quality measures and independent variable of modular neuromuscular parameters

| Gait Features | SI parameters [%] | Multiple regression model | F-value | p-value | $R^2$ | $adjusted\ R^2$ |
|---|---|---|---|---|---|---|
| Spatiotemporal characteristics | Step length | $SI_{SL} = 8.422 - 10.29VAF_{AS} + 14.01A_{RF,AS}$ | 8.26 | < 0.001 | 0.56 | 0.49 |
| | Step time | - | - | - | - | - |
| Limb kinematics | Leg extension angle | $SI_{LEA} = -0.98 + 15.18A_{RF,AS}$ | 9.16 | < 0.001 | 0.40 | 0.35 |
| | Limb length | $SI_{LL} = -16.52 + 17.82VAF_{AS,3}$ | 5.96 | < 0.05 | 0.30 | 0.25 |
| | Footpath area | $SI_{FPA} = -18.98 + 20.52VAF_{AS,3}$ | 7.73 | < 0.05 | 0.36 | 0.31 |
| Joint kinematics | Hip flex/ex | $SI_{Hip,FE} = -1.82 + 2.27VAF_{US,1} + 4.91A_{RF,US}$ | 13.0 | < 0.001 | 0.67 | 0.62 |
| | Hip abd/add | $SI_{Hip,AA} = -2.19 + 2.56VAF_{US,1} + 1.76A_{VL,AS}$ | 8.39 | < 0.01 | 0.56 | 0.50 |
| | Hip int/ext ro. | $SI_{Hip,IE} = 0.46 - 2.25A_{TA,US}$ | 8.39 | < 0.01 | 0.39 | 0.35 |
| | Knee flex/ex | $SI_{Knee,FE} = -18.1 + 19.24VAF_{AS,3}$ | 9.91 | < 0.01 | 0.41 | 0.37 |
| | Ankle dorsi/plantar | - | - | - | - | - |

*SL* – step length, *LEA* – leg extension angle, *LL* – limb length, *FPA* – footpath area, *Hip,FE* – hip flexion/extension, *Hip,AA* – hip abduction/adduction, *Hip,IE* – hip internal/external rotation, *Knee,FE* – knee flexion/extension, *VAF* – variability accounted for, *A* – area under EMG envelope curve, *RF* – rectus femoris, *VL* – vastus lateralis, *TA* – tibialis anterior

504 **Fig 1.**

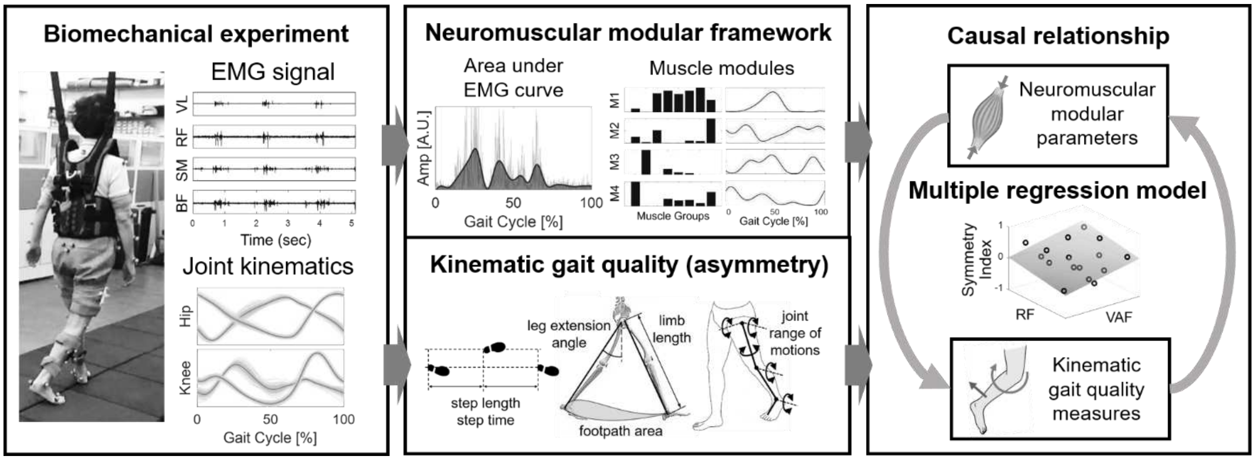


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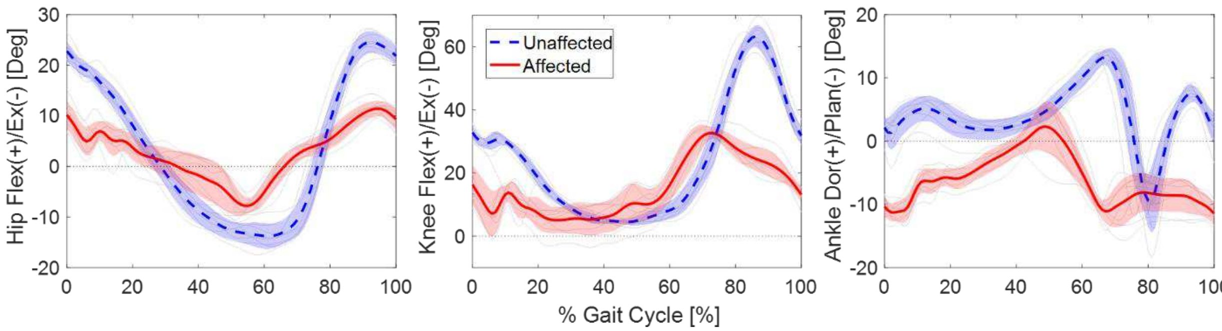
**Fig 2.**



Hip Flex(+)/Ex(-) [Deg]
Knee Flex(+)/Ex(-) [Deg]
Ankle Dor(+)/Plan(-) [Deg]
Unaffected
Affected
% Gait Cycle [%]
30
20
10
0
-10
-20
60
40
0
20
40
60
80
100

**Fig 3.**

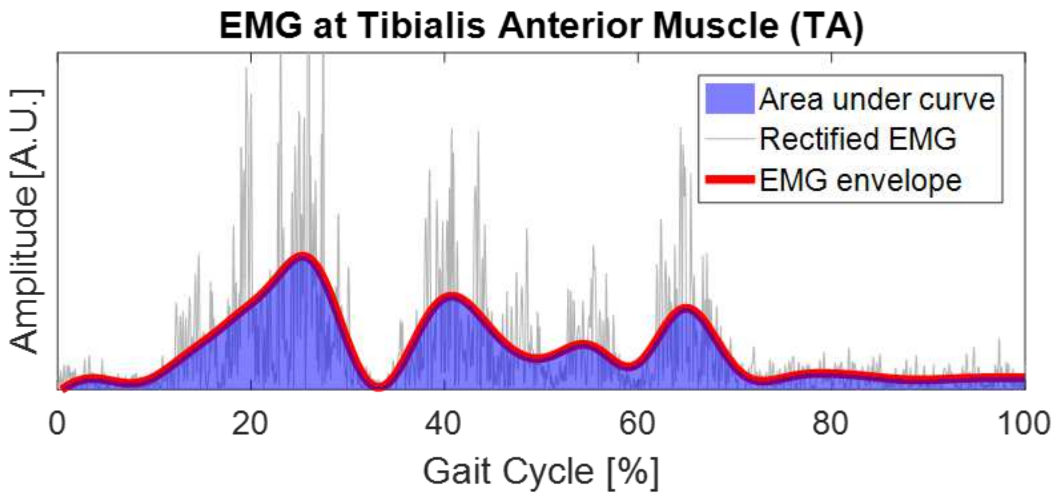
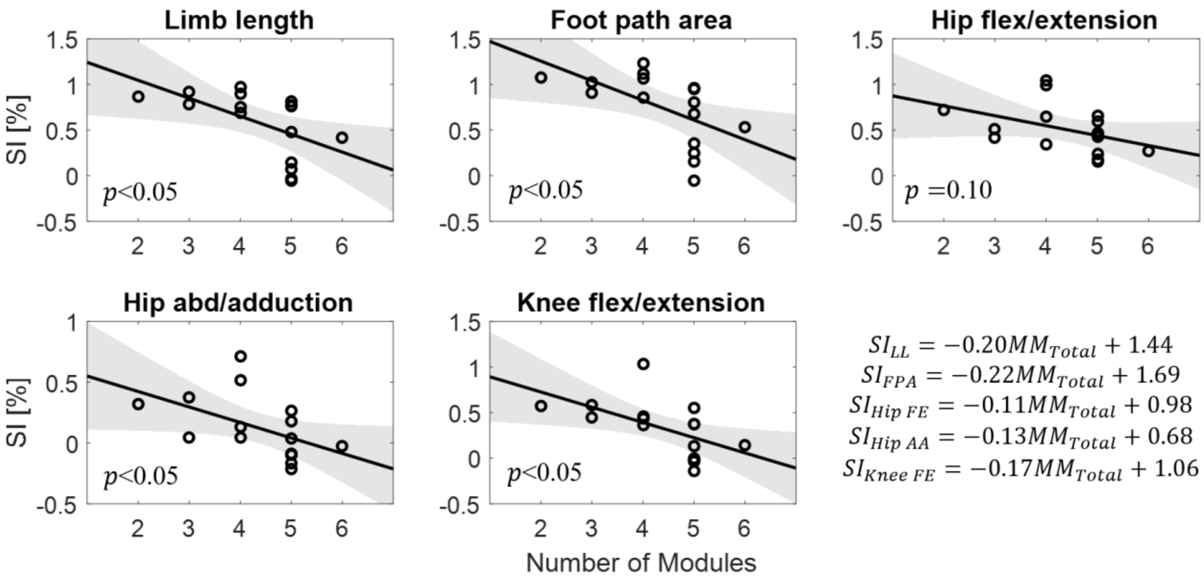
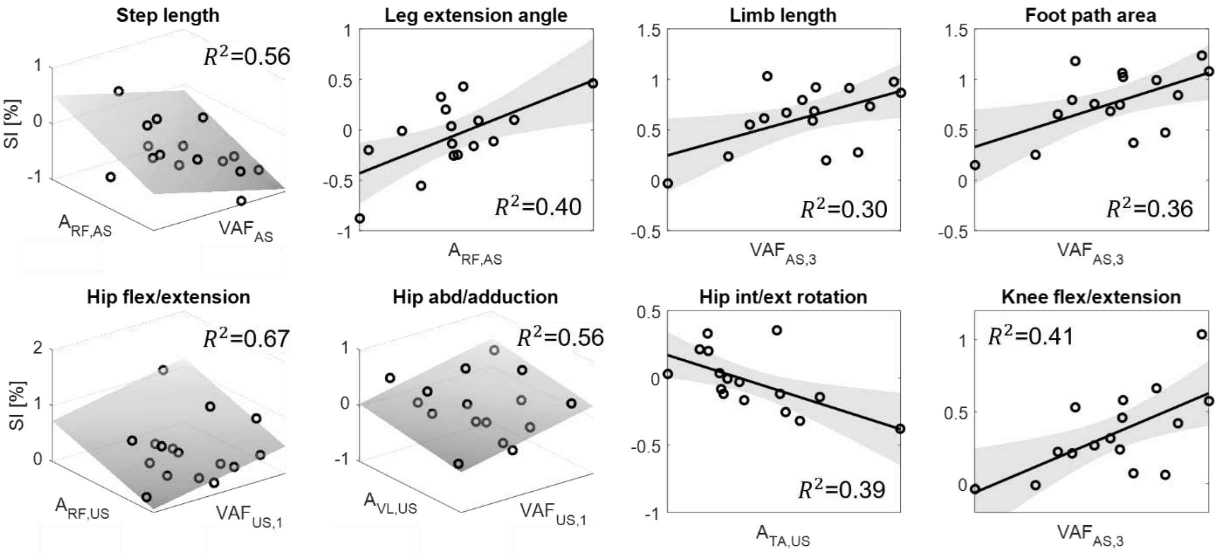

EMG at Tibialis Anterior Muscle (TA)
Area under curve
Rectified EMG
EMG envelope
Amplitude [A.U.]
0
20
40
60
80
100
Gait Cycle [%]

**Fig 4.**


Limb length
Foot path area
Hip flex/extension
Hip abd/adduction
Knee flex/extension
SI [%]
Number of Modules
p<0.05
p<0.05
p =0.10
p<0.05
p<0.05
$SI_{LL} = -0.20MM_{Total} + 1.44$
$SI_{FPA} = -0.22MM_{Total} + 1.69$
$SI_{Hip\ FE} = -0.11MM_{Total} + 0.98$
$SI_{Hip\ AA} = -0.13MM_{Total} + 0.68$
$SI_{Knee\ FE} = -0.17MM_{Total} + 1.06$

517 **Fig. 5.**


Step length
$R^2$=0.56
SI [%]
$A_{RF,AS}$
$VAF_{AS}$
Leg extension angle
$R^2$=0.40
$A_{RF,AS}$
Limb length
$R^2$=0.30
$VAF_{AS,3}$
Foot path area
$R^2$=0.36
$VAF_{AS,3}$
Hip flex/extension
$R^2$=0.67
SI [%]
$A_{RF,US}$
$VAF_{US,1}$
Hip abd/adduction
$R^2$=0.56
$A_{VL,US}$
$VAF_{US,1}$
Hip int/ext rotation
$R^2$=0.39
$A_{TA,US}$
Knee flex/extension
$R^2$=0.41
$VAF_{AS,3}$

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# Figures

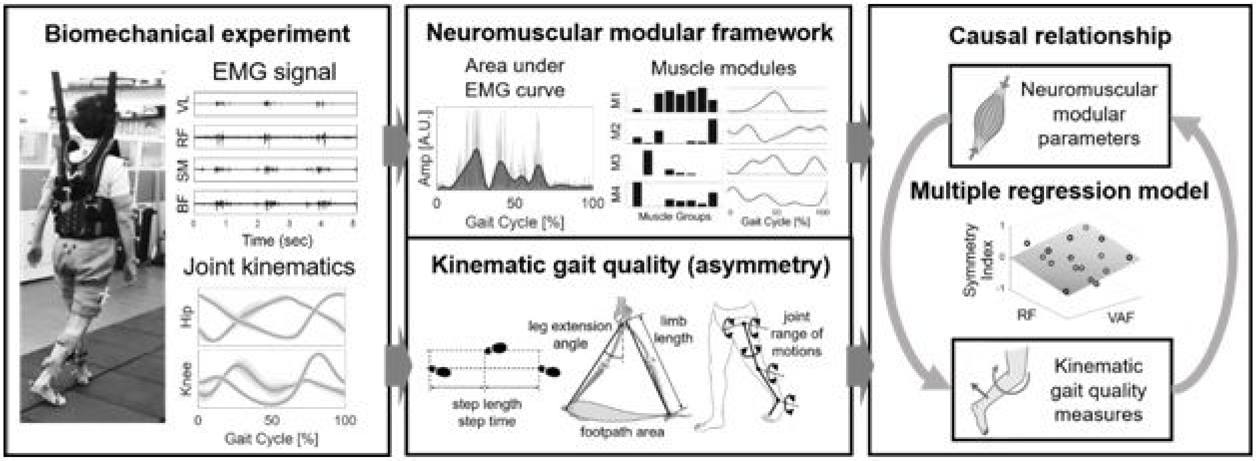



Figure 1

Overview of the study.

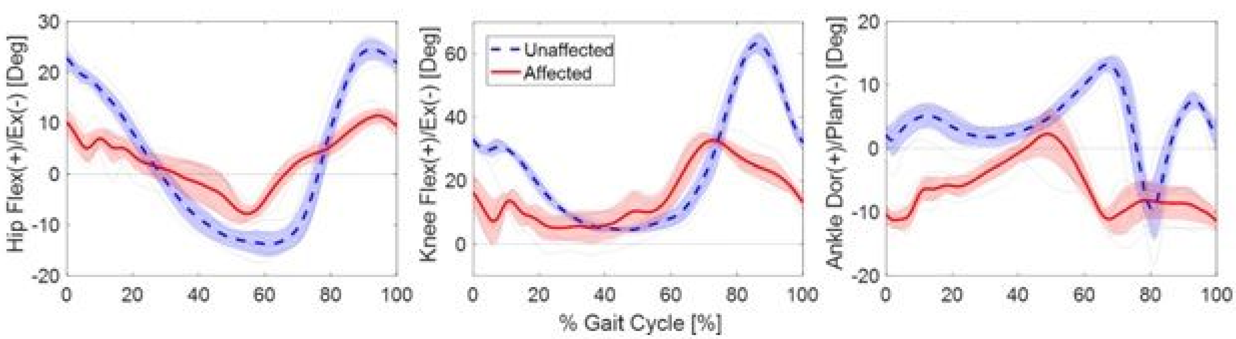



Figure 2

Example joint angle trajectories of a single gait cycle (heel strike to heel strike) in sagittal plane, hip flexion/extension (left), knee flexion/extension (middle), and ankle dorsi/plantarflexion (right).

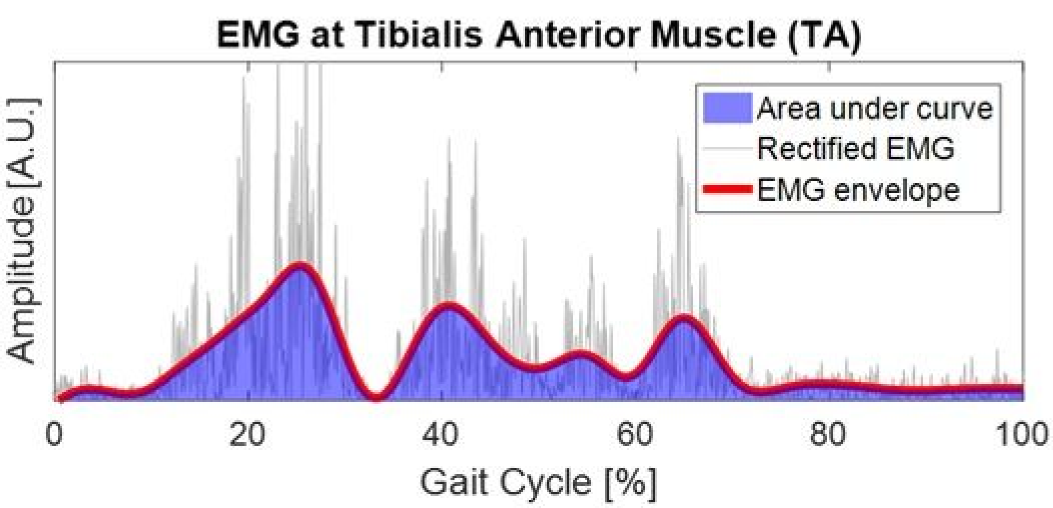
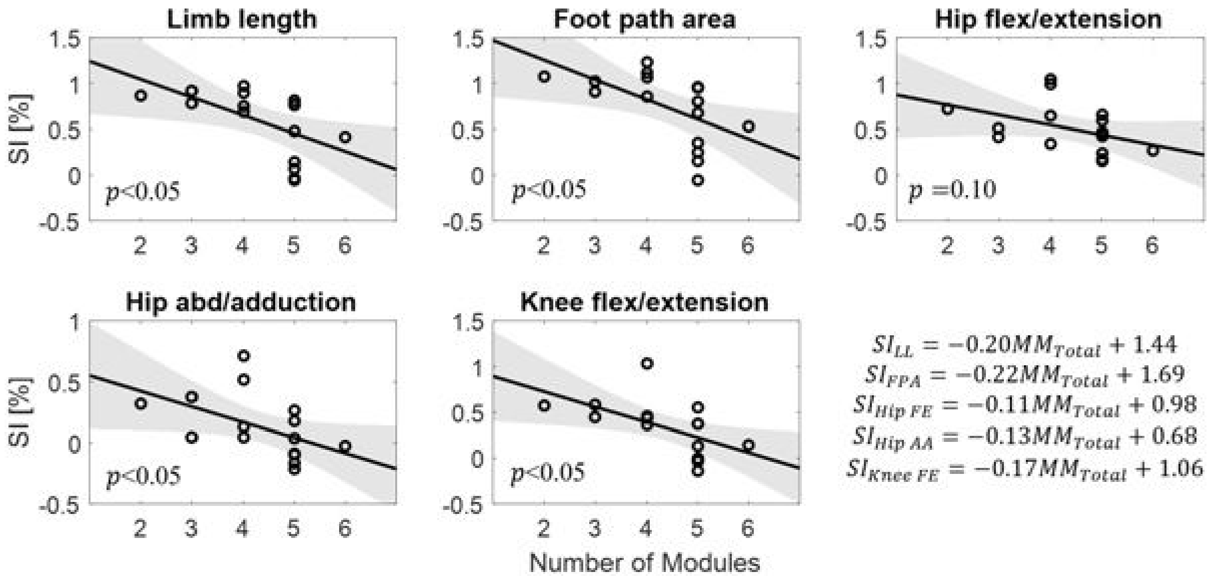


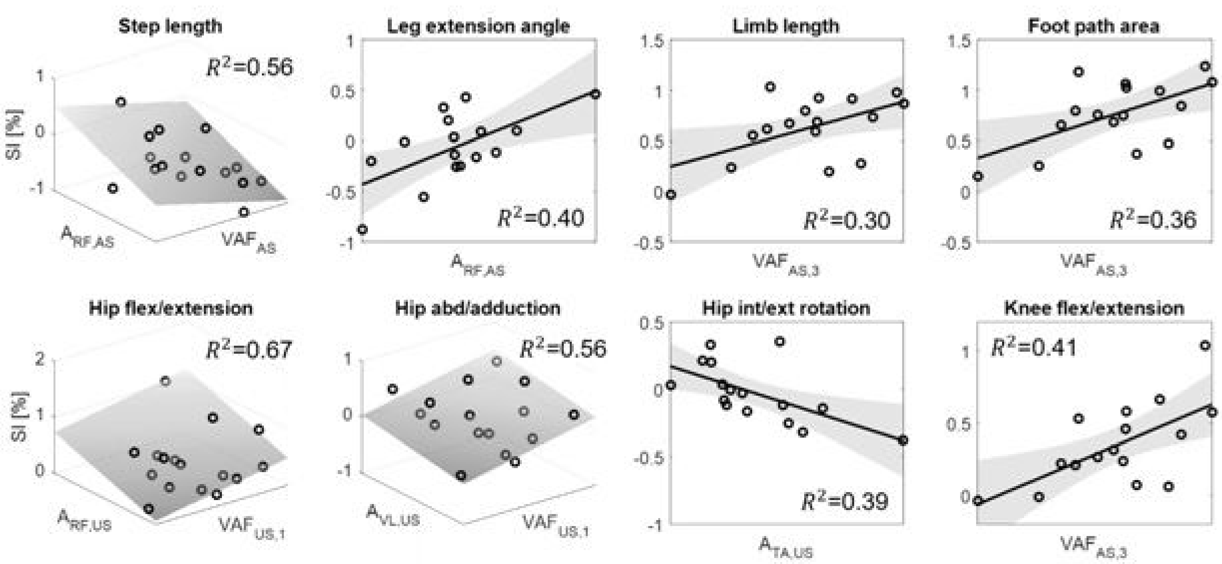

Figure 3

Example area under the EMG envelope curve oftibialis anterior muscle from participant P1. A.U. in the y-axis indicates arbitrary unit.




## Figure 4

Symmetry index (SI) of significant gait parameters including limb length (LL), footpath area (FPA), hip flex/extension (Hip FE), hip abd/adduction (Hip AA) and knee flex/extension (Knee FE)with increased total number of muscle modules at both sides (MM_Total). Linear regression models (bottom, right) were fitted on each gait parameter. The shaded area indicates 95% confidence interval.




## Figure 5

Regression models with selected independent variables (see Table 3)from stepwise multiple regression. Note that a plane in three-dimensional space is illustrated with two independent variables for step length, hip flex/extension and hip abd/adduction.