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Normative EMG patterns of ankle muscle co-contractions in school-age children during gait / Di Nardo, Francesco; Mengarelli, Alessandro; Burattini, Laura; Maranesi, Elvira; Agostini, Valentina; Nascimbeni, Alberto; Knaflitz, Marco; Fioretti, Sandro. - In: GAIT & POSTURE. - ISSN 0966-6362. - ELETTRONICO. - 46:(2016), pp. 161-166. [10.1016/j.gaitpost.2016.03.002]

Availability:

This version is available at: 11583/2638672 since: 2016-09-21T09:22:07Z

Publisher:

Elsevier

Published

DOI:10.1016/j.gaitpost.2016.03.002

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<http://dx.doi.org/10.1016/j.gaitpost.2016.03.002>

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Normative EMG patterns of ankle muscle co-contractions in school-age children during gait

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Key Words: surface electromyography, ankle flexor muscles, statistical gait analysis, antagonist muscles, children

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ABSTRACT

Purpose: The study was designed to assess the co-contractions of tibialis anterior (TA) and gastrocnemius lateralis (GL) in healthy school-age children during gait at self-selected speed and cadence, in terms of variability of onset-offset muscular activation and occurrence frequency.

Methods: Statistical gait analysis, a recent methodology performing a statistical characterization of gait by averaging spatio-temporal and sEMG-based parameters over numerous strides, was performed in 100 healthy children, aged 6-11 years. Co-contractions were assessed as the period of overlap between activation intervals of TA and GL.

Results: On average, 165 ± 27 strides were analyzed for each child, resulting in approximately 16,500 strides. Results showed that GL and TA act as pure agonist/antagonists for ankle plantar/dorsiflexion (no co-contractions) in only $19.2 \pm 10.4\%$ of strides. In the remaining strides, statistically significant ($p < 0.05$) co-contractions appear in early stance ($46.5 \pm 23.0\%$ of the strides), mid-stance ($28.8 \pm 15.9\%$), pre-swing ($15.2 \pm 9.2\%$), and swing ($73.2 \pm 22.6\%$). This significantly increased complexity in muscle recruitment strategy beyond the activation as pure ankle plantar/dorsiflexors, suggests that in healthy children co-contractions are likely functional to further physiological tasks as balance improvement and control of joint stability.

Conclusions: This study represents the first attempt for the development in healthy children of a normative dataset for GL/TA co-contractions during gait, achieved on an exceptionally large number of strides in every child and in total. The present reference frame could be useful for discriminating physiological and pathological behavior in children and for designing more focused studies on the maturation of gait.

Introduction

Surface electromyography (sEMG) acquired from lower-limb musculature is commonly used during clinical gait analysis in adult and pediatric populations. A wide literature reported normative EMG data in adults during walking [1-3]. Some studies were carried out to obtain a reference sEMG dataset also for a pediatric population [4-7]. Shiavi et al. [4] reported normative data for childhood EMG gait patterns, based on the computing of linear envelopes of the electromyograms measured from seven lower-extremity muscles. More recently, Chang et al. [5] indicated the range of normal sEMG

activity in children and Schwartz et al. [6] proposed normative patterns to evaluate the effect of walking speed on gait of typically developing children. Agostini et al. [7] performed a statistical analysis on numerous strides on a population of 100 healthy children, in order to define a reliable normative dataset of muscle activation patterns in children. Further studies focused on the maturation of gait, suggesting that the mature pattern of muscle recruitment is usually achieved by an age of six to eight years in normally developing children [8-10]. Greater co-activation of antagonistic leg muscles during the stance phase (in particular, the ankle muscles) was identified as one of the typical features of immature gait [9,11]. Co-contraction, or the simultaneous activation of agonist and antagonist muscles during the execution of a task, was reported to occur in children, to a limited extent, in those activities requiring motor coordination and joint stability, including walking and running [12-14]. Moreover, in children co-contraction was also implicated as a cause of inefficient or abnormal movement, especially in some neuromuscular pathologies such as spastic cerebral palsy [15-16]. Thus, a systematic study on co-contraction in children could be valuable in order to give a further insight in the process of maturation of gait and in the comprehension of some neuromuscular children pathologies, such as spastic cerebral palsy. Recently, a “normality” reference frame for TA/GL co-contraction was reported in young healthy subjects during gait [17]. This study identified four different occurrences of co-contraction during gait cycle: in early stance, mid-stance, pre-swing and late swing. To our knowledge, a similar study in children is not present in literature. The aim of the present study was, therefore, the quantitative assessment of Tibialis Anterior (TA) vs. Gastrocnemius Lateralis (GL) co-contractions in 100 healthy children aged 6-11 years during gait at self-selected speed and

cadence, in order to develop a reference frame in terms of variability of onset-offset muscular activation and occurrence frequency.

Materials and Methods

Signal acquisition

Gait data from 100 healthy children (49 females and 51 males, 6-11 years) were retrospectively analyzed (age 9.0 ± 1.4 years; height 133 ± 9 cm; mass 30.6 ± 6.7 kg) [7]. Exclusion criteria included history of neurological disorders, orthopedic surgery, acute/chronic pain or pathology and abnormal gait (toe walking, early heel rise, planovalgus foot, etc.). The present research was undertaken in compliance with the ethical principles of Helsinki Declaration.

Signals were acquired (sampling rate: 2 kHz; resolution: 12 bit) and processed by the multichannel recording system, Step32, Medical Technology, Italy. Three foot-switches (Step32, Medical Technology, Italy; size: $10 \times 10 \times 0.5$ mm; activation force: 3 N) were attached beneath heel, first and fifth metatarsal heads of each foot. An electro-goniometer (Step32, Medical Technology, Italy; accuracy: 0.5°) was attached to the lateral side of each lower limb for measuring knee-joint angles in sagittal plane (Fig. 1B). The electrogoniometer was directly affixed to the skin using bi-adhesive tape, with endplates attached in correspondence to proximal tibia and distal femur, respectively. sEMG signals were detected with single-differential probes with fixed geometry constituted by Ag-disks (manufacturer: Medical Technology, diameter: 4 mm; interelectrode distance: 12 mm, gain: 1000, high-pass filter: 10 Hz, 2 poles). sEMG signals were further amplified and low-pass filtered (450 Hz, 6 poles) by the recording system [18]; an overall gain, ranging

from 1000 to 50000, could be chosen to suit the need of the specific muscle observed (input referred noise $\leq 1 \mu\text{V}_{\text{rms}}$). sEMG probes were applied over Tibialis Anterior (TA) and Lateral head of Gastrocnemius (GL), bilaterally. Probes were positioned according to Winter's guidelines [14]. Crosstalk between TA and GL was checked for by visual inspection of raw signals; thanks to the use of probes with short interelectrode distance (12 mm) no problem of crosstalk was detected between TA and GL. Participant set-up is shown in Fig. 1. Then, children were instructed to walk barefoot for 2.5 min, at their natural pace, back and forth over a 10-m straight track. Natural pace was chosen since walking at a self-selected speed improves the repeatability of sEMG data [19].

Signal processing

Footswitch signals were debounced, converted to four levels, Heel contact (H), Flat foot contact (F), Push-off (P), Swing (S), and processed to segment and classify the different gait cycles [20].

Electrogoniometric signals were low-pass filtered (FIR filter, 100 taps, cut-off frequency 15 Hz) [21]. Knee angles in sagittal plane along with sequences and durations of gait phases derived by basographic signal, were used by a multivariate statistical filter (Hotelling t-test, $\alpha=0.05$), to detect outlier cycles like those relative to deceleration, reversing, and acceleration [22]. Cycles with improper sequences of gait phases (i.e. different from H-F-P-S sequence), not corresponding to straight walking and with abnormal timing and knee angles, with respect to a mean value computed on each single subject, were discarded [20]. Visual inspection was also used to confirm the effectiveness of the automatic procedure.

sEMG signals were high-pass filtered (FIR filter, 100 taps, cut-off frequency of 20 Hz) and processed by a double-threshold statistical detector, allowing a user-independent assessment of muscle activation intervals [23]. This technique [23] consists of selecting a first threshold ζ and observing m successive samples: if at least r_0 (second threshold) out of successive m samples are above ζ , the presence of the signal is acknowledged. Values of the three parameters ζ , r_0 , and m are selected to jointly minimize the false-alarm probability value and maximize the detection probability for each specific signal-to-noise ratio. The setting of ζ is based on the assessment of background noise level, as a necessary input parameter. Furthermore, the double-threshold detector requires estimating the signal-to-noise ratio in order to fine tune r_0 . Background noise level and signal-to-noise ratio, necessary to run double-threshold algorithm, is estimated for each signal by Step32 system, using a statistical approach [24]. Muscular co-contractions were quantified by assessing the overlapping period among activation intervals of the considered muscles, in the very same strides [25]. An example of co-contraction assessed from raw signals of a representative subject is reported in Fig. 2. Overlapping periods ≤ 30 ms were not considered in co-contraction computation, since muscle activation ≤ 30 ms has no effect in controlling the joint motion during gait [23].

Statistical gait analysis

Statistical gait analysis (SGA) is a recent methodology, which performs a statistical characterization of gait analyzing spatial-temporal and sEMG-based parameters over numerous (hundreds) strides, collected during the same walking trial [7,22]. SGA relies on the fact that the number of muscle activations is cycle dependent, so that averaging should be performed only over onset/offset instants of cycles including the same number

of activations, i.e. belonging to the same activation modality. Activation modality is defined as the number of times a muscle activates during a single gait cycle (n -activation modality consists of n activation intervals for the considered muscle, during a single gait cycle). Mean activation intervals (normalized with respect to gait cycle) for each activation modality are achieved, according to the following steps. First, muscle activation intervals relative to each gait cycle are identified, computing muscle onset/offset time instants [23,26], as previously described. Then, muscle activations are grouped according to their modality. Eventually, the onset/offset time instants of each activation modality are averaged over the 100 subjects. Onset/offset time instants are normalized with respect to gait cycle duration, to provide mean activation intervals as a percentage of gait cycle. SGA was performed by Step32-system software.

Data are reported as means \pm standard deviation (SD). The Lilliefors test was used to evaluate the hypothesis that each data vector had a normal distribution. Since only comparisons among more than two not normally distributed samples were performed, Kruskal-Wallis test followed by multiple comparison test, were used. Statistical significance was set at 5%.

Results

For each subject, a mean of 165 ± 27 strides was considered for the study, after discarding the strides not following the H-F-P-S foot-switch pattern and/or being outlier cycles relative to deceleration, reversing, and acceleration of gait direction changes. Thus, a total of 16401 strides were selected. H-phase lasted $5.9\pm 1.8\%$, F-phase $32.5\pm 5.6\%$, P-phase $22.1\pm 5.4\%$ and S-phase $39.6\pm 3.2\%$ of gait cycle.

The SGA of myoelectric signal indicated that muscles show a different number of activation intervals in different strides of the same trial. Details of activation intervals are reported in Table 1 for GL and in Table 2 for TA.

No overlapping between TA and GL activation intervals (i.e. no co-contractions) was observed in $19.2\pm 10.4\%$ of strides, where GL presented a single activation and simultaneously TA presented 2 or 3 activations in the whole gait cycle (Fig. 3A). In the further strides characterized by 1-activation modality for GL, a co-contraction from $30.4\pm 10.1\%$ to $40.5\pm 10.3\%$ of gait cycle was detected (Fig.3A).

In the strides characterized by GL double activation (Fig. 3B), TA/GL superimpositions were observed during stance from $7.2\pm 4.1\%$ to $11.9\pm 8.8\%$ and from $30.5\pm 5.7\%$ to $37.0\pm 7.6\%$ of gait cycle. During swing, GL superimposed TA activity from $65.9\pm 12.1\%$ to $80.0\pm 10.0\%$ (TA 2-activation modality), from $65.9\pm 12.1\%$ to $69.0\pm 7.2\%$ (TA 3-activation modality) and from $65.9\pm 12.1\%$ to $75.4\pm 2.8\%$ (TA 4-activation modality) of gait cycle.

In the strides with GL triple activation (Fig. 3C), TA/GL superimpositions were observed in early stance, for all the TA activation modalities. Further overlapping intervals were detected from $32.7\pm 9.7\%$ to $41.9\pm 9.5\%$ and from $50.7\pm 6.9\%$ to $55.3\pm 6.6\%$. During swing, a total superimposition with GL activation (from $87.3\pm 8.3\%$ to $94.5\pm 6.9\%$) was detected, for all the TA activation modalities.

Considering the GL modalities of activation all together (100% of strides), four different occurrences of co-contraction were detected during gait cycle: in early stance, mid-stance, pre-swing and swing. Since not each data vector had a normal distribution (Lilliefors test), Kruskal-Wallis test, followed by multiple comparison test, was used to test eventual differences among occurrence frequencies of the four co-contractions. Co-

contraction detected during swing showed a greater occurrence frequency ($73.2\pm 22.6\%$, $p<0.001$), compared with the other three co-contractions. Co-contraction detected during pre-swing showed a smaller occurrence frequency ($15.2\pm 9.2\%$, $p<0.001$), compared with the other three co-contractions. A significant difference was observed also between the mean occurrence frequency of co-contractions detected in early stance and in mid-stance ($46.5\pm 23.0\%$ vs. $28.8\pm 15.9\%$, $p<0.001$).

Discussion

The study was designed to quantify the co-contractions of GL and TA in healthy children during gait at self-selected speed and cadence, in terms of onset-offset muscular activation and percentage of strides where the considered activation is observed. To this aim, SGA of sEMG signals from numerous strides per each subject was performed in 100 healthy children, aged 6-11 years. Different sEMG-based methods were proposed for quantification of muscular co-contractions, considering both temporal and amplitude parameters [27]. Some authors, however, disapprove the use of amplitude parameters for inter-subject comparison, given that their assessment could be affected by the effect of electrode location and volume conductor inhomogeneities [28]. Thus, in the present study sEMG signals were studied by analyzing temporal parameters only.

The muscle-activation intervals followed the typical pattern reported for children during gait [4,8]. According to previous studies in children [7] and young adults [29], our analysis highlighted that both GL and TA show different modalities in number of activations and in timing of signal onset/offset, in different strides of the same walking trial. This finding was reported both in adults and children also for thigh muscles [7,22,30-

32]. This suggests that it is worth considering not only the activation patterns of each muscle, but also their occurrences.

In child walking, as in adult, the main task of GL and TA is to oppose each other in action causing sagittal plane ankle movement [2]. In accomplishing this task, most of the myoelectric activation is centered in stance for GL and in swing for TA, with no overlapping between activation intervals, and, thus, no co-contraction. Here, the only strides ($19.2\pm 10.4\%$) with no overlapping between TA and GL activations were those where GL simultaneously presented a single activation and TA showed 2 or 3 activations, in gait cycle (Fig. 3A). Only in these strides, GL and TA should be considered as performing an agonist/antagonist activation for ankle plantar/dorsiflexion. Modalities of activation and percentage of strides with no co-contractions are comparable to what reported for young adults [17].

It was reported that children (6-8 years) show a within session EMG variability twice larger than adults [11]. Although children in this age-range can be considered to have a mature walk [4,8], Granata et al. [11] hypothesize that variability about the mean performance continues to develop for many years and stable locomotion may be achieved despite significant variability in the muscle recruitment patterns. The hypothesis of large sEMG variability in children is supported also by a recent study [7]. In this study, the observation in children of a TA activity during mid-stance, usually not reported in healthy adults, was recognized as one of the main factors producing the variability. One further factor was the alternation of presence/absence of a swing-phase activity for GL. The occurrence of these two activations is fundamental to explain the large amount of superimpositions between GL and TA activations detected in $80.8\pm 17.1\%$ of the strides of the present population. Indeed, the TA mid-stance activity (4-activation modality in

Figure 3) overlaps the typical GL activation as ankle plantar-flexor, producing a co-contraction in $28.8\pm 15.9\%$ of strides. Thus, in this phase, TA and GL co-contract for controlling balance during single support and contralateral limb swing [29]. This finding is supported by Olney's study [13] that reported lower level co-contractions during mid-stance. The percentage of this co-contraction is comparable to what reported for young adults [17]. Moreover, the GL activity in swing, reported also in [8], is related to the possible activation of GL as foot-invertor muscle [33], and is superimposed to the typical TA activation as ankle dorsi-flexor. It is likely that in this phase, GL and TA do not oppose each other in action for causing sagittal plane movement, but act in synergy for the correct foot positioning, in preparation of following heel strike [17]. The co-contraction of GL and TA in this phase was detected in the $73.2\pm 22.6\%$ of strides, resulting the most common one among the detected co-contractions. This percentage results about 10% higher than that reported in young adults [17]. These findings seem to suggest a stabilizing control in children even more responsive than in adults, in order to prevent excess dorsiflexion and control foot positioning. This supports the hypothesis that a young neurocontrol system can operate on more degrees of freedom [11].

Two further occurrences of co-contractions were detected during gait cycle. Starting from the beginning of gait cycle, the first overlapping between GL and TA activations was detected in early stance, at the transition from double support to single support (Figures 3A-3B). These co-contractions are useful to stabilize and smooth the double-to-single support transition [12,34]. In every child, early-stance co-contraction did not exceed the length of 10% of gait cycle. This finding matches with the minimal co-contraction reported in adults in this phase of gait cycle, both in terms of amplitude [34] and in terms of duration [17]. On the other hand, occurrence frequency is 50% higher

than that reported in young adults [17], confirming that children have to increase limb stability. The GL activation detected in pre-swing (second activation in Fig. 3C), likely occurring to produce knee flexion and/or for avoiding possible knee hyperextensions [14], overlaps the TA activation as ankle dorsi-flexor in preparation for swing in $15.2\pm 9.2\%$ of strides (3-activation modality TA in Fig. 3C). Presence of TA/GL co-activations in pre-swing in a low percentage of strides matches with findings reported in adults [13,17]. However, this superimposition should not be considered as a real co-contraction (i.e. simultaneous contraction of agonist and antagonist muscles crossing a joint), because TA and GL work on different joints [14].

The occurrence of TA/GL co-contraction throughout gait cycle was reported by many studies on healthy adults [12-13,17,35]. Attempts of describing co-contractions during normal gait in children were done [36-38], but mainly for comparative purpose and in a limited numbers of subjects and strides. To our knowledge, the present analysis represents the first attempt for providing a “normality” reference frame for co-contraction in children, achieved on an exceptionally numerous strides in every subject and in total. A further merit of the study consists in quantifying the physiological variability of the co-contraction phenomenon not only in terms of the onset-offset muscular activation but also in terms of the occurrence frequency, a parameter seldom considered because of the few strides analysed in classic EMG studies [39]. Since ankle-muscle co-contractions were mainly reported in pathological populations, especially in some neuromuscular pathologies such as spastic cerebral palsy [15,16,37,38], the present reference frame could be useful for discriminating physiological and pathological behavior in children. Moreover, thanks to its selectivity, it could be suitable for designing more focused gait

studies on the effect of age on variability of physiological co-contraction and on the maturation of gait.

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TABLE 1

Gastrocnemius lateralis	First activation (% gait cycle)		Second activation (% gait cycle)		Third activation (% gait cycle)	
	ON	OFF	ON	OFF	ON	OFF
1-activation mod	14.1±8.1	49.7±6.8				
2-activation mod	7.2±4.1	37.0±7.6	66.9±12.1	80.0±10.0		
3-activation mod	2.8±3.1	20.4±10.1	32.7±9.7	55.3±6.6	87.3±8.3	94.5±4.9

Activation intervals of GL in its main modalities of activation. Values (mean ± standard deviation, SD) are expressed as the time instants, in percentage of gait cycle, of signal onset and offset.

TABLE 2

Tibialis anterior	First activation (% gait cycle)		Second activation (% gait cycle)		Third activation (% gait cycle)		Fourth activation (% gait cycle)	
	ON	OFF	ON	OFF	ON	OFF	ON	OFF
Panel 1								
2-activation mod	1.1±1.0	10.7±8.6	56.1±4.4	99.5±0.5				
3-activation mod	0.2±0.2	8.9±5.1	51.4±7.5	68.3±8.5	82.0±8.3	99.8±0.2		
4-activation mod	0.0±0.0	8.6±6.0	30.4±10.1	40.5±10.3	58.2±7.1	74.7±5.9	86.6±6.7	100±0.0
Panel 2								
2-activation mod	1.7±1.6	11.9±8.8	56.3±3.8	99.3±0.6				
3-activation mod	0.1±0.1	7.2±5.1	51.1±6.5	67.9±7.2	81.5±7.7	99.8±0.2		
4-activation mod	0.0±0.0	8.0±3.6	30.5±5.7	42.2±6.6	59.3±3.4	75.4±2.8	88.3±3.2	99.9±0.1
Panel 3								
2-activation mod	0.9±0.9	9.5±6.0	56.4±6.7	99.6±0.3				
3-activation mod	0.2±0.2	9.8±5.3	50.8±6.9	67.8±8.2	80.9±8.1	99.8±0.2		
4-activation mod	0.0±0.0	7.6±3.7	30.4±10.7	41.9±9.5	57.5±3.8	74.1±3.7	86.6±3.5	100±0.0

Activation intervals of TA in the very same strides where GL occurs in the 1-activation modality (Panel 1), in the 2-activation modality (Panel 2), and in the 3-activation modality (Panel 3). Values (mean ± standard deviation, SD) are expressed as the time instants, in percentage of gait cycle, of signal onset and offset.

Figure Captions

Fig. 1 Participant set-up: frontal (A), lateral (B) and rear view (C). Foot-switches, knee electrogoniometers and EMG probes are fixed to the subject, bilaterally.

Fig. 2 Example of co-contraction, assessed as the overlapping period between GL (1-activation modality) and TA (4-activation modality) raw signals of a representative subject. The co-contraction is highlighted by the grey box. Heel strike (H), Flat foot contact (F), Push-off (P) and Swing (S), provided by foot-switch data, are delimited by vertical dashed lines.

Fig. 3 Mean values of TA activation intervals (dark-gray bars) vs. percentage of gait cycle, detected in the strides where GL (light -gray bars) shows 1-activation (panel A), 2-activation (panel B) and 3-activation (panel C) modality, respectively. TA activation intervals are reported separately for the modalities with 2, 3 and 4 activations. TA/GL co-contraction is highlighted by dashed box. H, F, P and S phases are delimited by dashed gray vertical lines.

FIG. 1

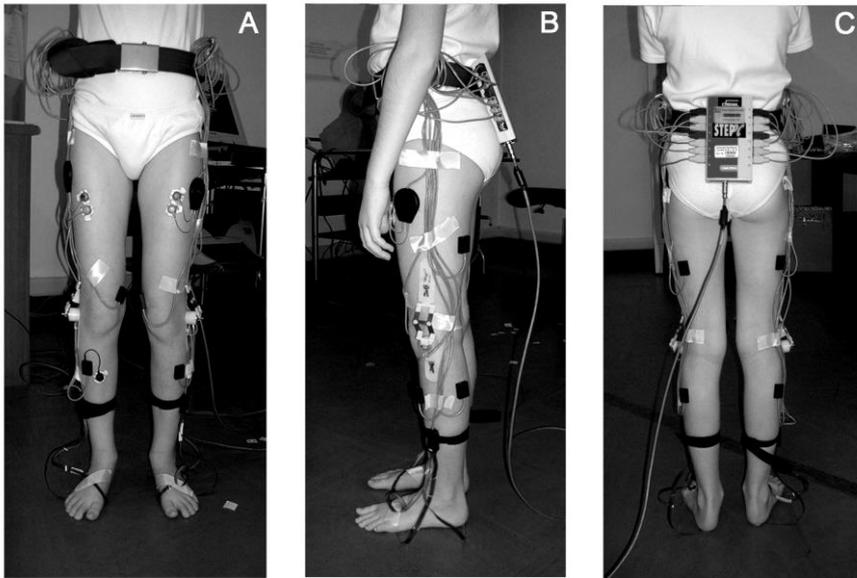


FIG. 2

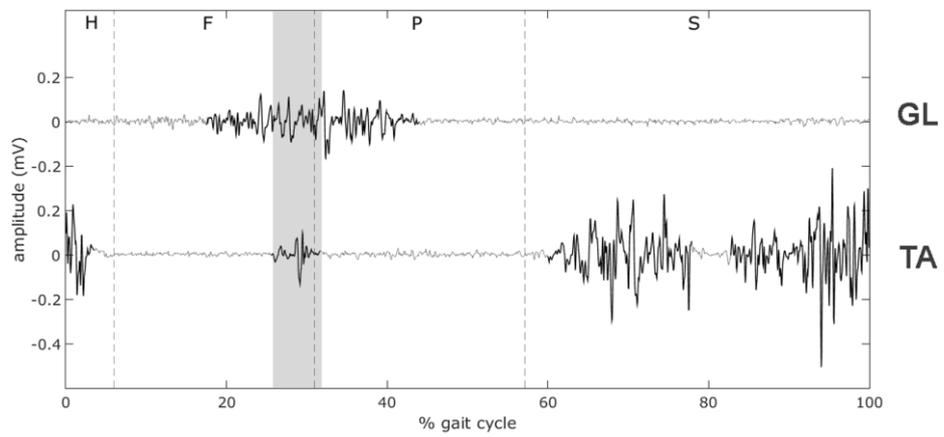


FIG. 3

