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Abstract

Gait analysis is widely used in clinics to study walking abnormalities for surgery planning, definition of rehabilitation protocols, and objective evaluation of clinical outcomes. Surface electromyography allows to study muscle activity non invasively and to evaluate the timing of muscle activation during movement. The aim of this study is to present a normative dataset of muscle activation patterns obtained considering a very large number of strides on a population of 100 healthy children aged 6-11 years. The activity of Tibialis Anterior, Gastrocnemius Lateralis, Vastus Medialis, Rectus Femoris and Lateral Hamstrings on both lower limbs was analyzed during a 2.5-minute walk at free speed. More than 120 consecutive strides have been analyzed for each child, resulting in approximately 28000 strides. Onset and offset instants are reported in terms of average value, standard deviation and confidence interval for each observed muscle. The analysis of a remarkably high number of strides for each participant allowed us to obtain the most recurrent patterns of activation during gait, demonstrating that a subject uses a specific muscle with different activation modalities even in the same walk. The knowledge of the various activation patterns and of their statistics will be of help in clinical gait analysis and will serve as reference in the design of future gait studies.

1. Introduction

Surface electromyography (SEMG) is an essential part of gait analysis. It supports clinicians with the objective assessment of muscular function during walking, especially when associated with dynamic of gait. Moreover, it provides insight on neural control during walking in terms of paretic and non-neural components, spasticity and co-contraction [1]. For example, in [2] dynamic EMG patterns are used to evaluate multilevel surgical treatments of children with cerebral palsy, while in [3] a similar analysis is used to evaluate the benefits of an ankle-foot orthosis. However, in order to correctly interpret kinesiological SEMG in pathological conditions, reliable normative data are required for comparison.

In clinical gait analysis [4-5] there is an extensive literature describing normative data for spatio-temporal parameters, joint rotations, ground reaction forces, net internal joint moments and joint power [6-8]. Various results have been reported on the maturation of gait in children [9-10] and some studies were carried out to obtain a reference SEMG dataset for a pediatric population [11-13].

An important limitation in classical gait analysis is the small number of consecutive gait cycles that is usually considered. For example, [14] reports a study on spatio-temporal parameters of 438 children considering a minimum of three consecutive steps. Chang et al. [11] report a study on a population of 87 children in which 4 to 24 (average 7.22 ± 2.69) strides per individual are considered. Patikas et al. [2] report a study on EMG patterns in children with cerebral palsy where 3-8 cycles are averaged.

A comprehensive description of muscle activity during a walk consisting of hundreds of consecutive steps is currently not available, for either an adult or pediatric population. Most studies in this field are based on the use of ensemble average of the linear envelopes. Novel techniques for detecting muscle activation intervals without the need of linear envelope extraction [15] and for segmenting the foot-switch signals [16] are available. For a systematic comparison of different methods of EMG onset detection see Ref. [17].

The aim of this work is to overcome the described limitations by applying the techniques cited above to consider more than a hundred of consecutive strides for each subject. We present a reference dataset obtained on a population of school-age children.

2. Materials and methods

2.1 Subjects

We analyzed a population of 100 children (6 to 11 years), 51 males and 49 females. Table 1 reports a summary of data describing the population. Children with orthopedic or neurological problems altering gait parameters were not included in the study. Parental consent and child assent were obtained prior to the participation in the study.

2.2 Recording system and signal acquisition

Signals were acquired by means of a multichannel recording system for statistical gait analysis (Step32, DemItalia, Italy). Each subject was instrumented with foot-switches, knee goniometers, and SEMG probes. Three foot-switches (size: 10 mm × 10 mm × 0.5 mm; activation force: 3 N) were attached beneath the heel, the first and the fifth metatarsal heads of each foot. A goniometer (accuracy: 0.5 deg) was attached to the lateral side of each lower limb for measuring the knee joint angles in the sagittal plane. Surface EMG probes were attached to the skin over the Tibialis Anterior (TA), Gastrocnemius Lateralis (GL), Vastus Medialis (VM), Rectus Femoris (RF), and Lateral Hamstrings (LH), bilaterally. Probes were positioned according to the guidelines suggested by Winter [18].

We used single differential (SD) probes constituted by Ag-disks (manufacturer: DemItalia, diameter: 4-mm, interelectrode distance: 12 mm, gain: 1000, high-pass filter: 10 Hz, 2 poles).

EMG signals were further amplified and low-pass filtered by the recording system (450 Hz, 6 poles). An overall gain from 1000 to 50000 could be chosen to suit the need of the specific muscle observed (input referred noise: $\leq 1\ \mu V_{rms}$). Crosstalk was checked for by visual inspection. Crosstalk was suspected when two muscles in the same limb section showed simultaneous activity with similar amplitude modulation. In this case, double differential (DD) probes were used to further improve spatial selectivity and the DD signal was compared with the SD one. If the amplitude of the DD signal was significantly lower, crosstalk was confirmed and the signal discarded. DD probes were three-bar probes (bar diameter: 1 mm, bar length: 10 mm, interelectrode distance: 10 mm) with gain and filtering properties equal to those of the single differential probes. Signals were sampled at 2 kHz, converted into 12-bit words and transferred to the computer for real-time display and further processing.

After positioning sensors, children were instructed to walk barefoot for 2.5 minutes, 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 EMG data [19], while variability increases when subjects are required to walk abnormally slow [13, 20]. Table 1 reports cadence and normalized velocity [21] observed during the experimental sessions.

2.3 Signal processing

Foot-switch signals were debounced, converted to 4-level signals (Heel contact (H), Flat foot contact (F), Push off (P), Swing (S)) and processed to segment and classify the different gait cycles used by the subject. The misclassification probability was lower than 1 cycle over 100 [16].

Goniometric signals were low-pass filtered (FIR filter, 100 taps, cut-off frequency of 15 Hz) and then used by a multivariate statistical filter, along with gait phases duration, to discard outlier cycles, i.e., cycles with the proper sequence of gait phases (H-F-P-S) but with abnormal timing, like those relative to deceleration, reversing, and acceleration.

EMG signals were high-pass filtered (FIR filter, 100 taps, cut-off frequency of 20 Hz) and then processed by a double-threshold statistical detector that allows to obtain, in a user-independent way, the muscle activation intervals [15].

2.4 Statistical analysis

In this study only gait cycles consisting of the sequence of H-F-P-S were considered, obtaining a database of 11084 cycles for the left lower limb and 11179 for the right. More specifically, for each child a mean of 125.1 ± 21.0 strides has been considered for each lower limb. After outlier removal, a mean of 83.2 ± 15.6 strides was obtained for each child, and the average value of the H, F, P and S phases duration was calculated for each of them. Only strides relative to straight walk were then considered in our study. Then, for each walk and each muscle, we calculated the relative frequency of strides showing 1 to 5 activation intervals and averaged the on- and off-instants for each activation modality.

3. Results

The first result of this study is the observation that, in each subject, muscles show a different number of activation intervals during the same walk. This behavior is often disregarded in literature. Figure 1 shows EMG signals from the RF muscle of a subject displaying three different activation patterns consisting of two, three and four activation intervals in different strides of the same walk. It is important to obtain, for each muscle, the different activation patterns and how frequently they are observed. As an example, Fig. 2 reports, for the same subject, the percentage frequency of the different activation patterns during the walk.

Figure 3 provides a pictorial description of the results over the population. The horizontal bars are grey-level coded - at each percent of the gait cycle - according to the number of children in which a certain condition is observed. Black indicates that the condition is observed for all the children, while white indicates that the condition is never observed.

Fig. 3a describes the foot-contact timing over the population (4-level signal). The H-phase lasts 5.9 ± 1.8 % (percent of the gait cycle, mean and standard deviation). The F-phase lasts 32.5 ± 5.6 %. The P-phase lasts 22.1 ± 5.4 %. The S-phase lasts 39.6 ± 3.2 %.

Fig. 3b, 3c, 3d, 3e, 3f show the muscle activation intervals over the population for TA, GL, VM, RF and LH, expressed as a percent of the gait cycle (GC). The left vertical axis shows the number of activation intervals, from 1 to 5. The right vertical axis reports the relative frequency of each pattern, i.e. the number of strides in which a specific pattern is observed with respect to the total number of strides. The H, F, P, S phases (mean values over the population) are shown superimposed, delimited by dashed vertical lines.

Table 2 presents the same results numerically, separately for the left (L) and the right (R) lower limb. This choice was suggested by the results presented by Granata et al. [22] who found asymmetries of right versus left leg. The column labeled with "%" reports the relative frequency (with respect to the total number of strides) of each modality.

The most recurrent pattern of activation of TA (Fig. 3b), observed in 48% of strides, is characterized by 3 activations: a) a first activation during the heel rocker up to 9.3% GC, b) a second activation starting before toe off (48.8% GC) up to 65.3% GC, c) a third activation starting at 79% GC up to the next initial contact. The other two modalities, consisting of 2 and 4 activation intervals, are observed in 23% and 23% of strides, respectively. The 2-activation modality differs from the most common pattern for a) the prolonged activity during heel rocker up to 15.2% GC, b) the continuous activation during swing, from 60.5% GC up to the next initial contact. The 4-activation modality shows a shorter activation during loading response (7.6% GC) and a double activity during swing, starting at toe off. Moreover, in 5% of strides there are 5 activations and in 1% of strides is observed a single highly variable activation: the onset and offset instants are scattered throughout the gait cycle resulting in a continuous light-gray bar.

The most recurrent pattern of activation of GL (Fig. 3c), observed in 34% of strides, shows two activations: a) a first one starting after heel rocker ending (7.3% GC) and ending at the heel off (37.1% GC) and b) a second one from initial swing (66.9% GC) to the end of midswing (80.0% GC). The second most frequent modality (29% of strides) is characterized by 3 activations. The third modality (27% of strides) consists of a single activation.

VM (Fig. 3d) shows two activations in 57% of strides, around initial contact: the first one from heel strike to midstance (19.6% GC) and the second from terminal swing (83.7% GC) to the successive initial contact. Less frequent is a 3-activation modality (30% of strides) with an activation around heel off, other than the two major activations already described.

RF (Fig 3e) shows a 3-activation pattern in 48% of strides, at the beginning of gait cycle (0-17.9% GC), around foot off (46.4-59.2% GC) and in terminal stance (from 85.1% GC to the next initial contact). In 25% of strides the pattern is similar but without the activation at the transient between stance and swing, and in 18% of strides this third activation is split into two small activations around heel off (34.6-42.5% GC) and around foot off (56.7-67.1% GC).

LH, in 47% of strides, is active twofold in the gait cycle (Fig. 3f): the first at heel contact, up to heel off (27.4% GC), and the second at midswing (77.5% GC) up to the successive heel strike. The second most recurrent pattern (36% of strides) shows 3 activations: a) from heel strike to mid stance, similar to the previous one, but shorter (16.7% GC), b) from midstance (35.5% GC) to pre-swing phase (47.9% GC), c) from 79.6% GC to the successive initial contact.

There is no correlation among occurrences of the five different activation modalities of each muscle and age or preferred cadence of children in none of the conditions considered.

4. Discussion

Actually there is a lack of normative data when EMG patterns of activation are explored. In most cases, data provided by Perry [4] in adults are still the only reference most clinicians take into account. However the range of signal onset and offset with respect to the gait cycle is never provided quantitatively in terms of average value and standard deviation. Previous works by Sutherland [23] report pictorial bars of activation, but quantitative data are not available.

The variability of muscular timing during gait has been explained, in adults, in terms of effect of speed variation and intra-subject variability [4, 19, 20]. Moreover, there is evidence that within session EMG variability, in children aged 6-8 years, is twice than that of adults [22]. Although children in this age range can be considered to have a mature walk [10, 13], Granata et al. [22] 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.

In our results, if we look at the intervals in which muscles are active, we can roughly find the pattern usually known for each muscle. However, there are different modalities in the number of activations and in the timing of signal onset and offset.

In particular TA has, in most cases, the typical activation with onset just before toe off and full swing activity continuing up to initial stance. While these findings are in agreement with Schwartz et al. [12] with respect to the absence of activity during stance, they diverge from Sutherland [10] who reports activity of this muscle up to approximately 40% of stance. Only in 23% of strides, when a 4-activation modality is present, there is an activation around midstance lasting approximately 10% GC (see Table 2b). The hypothesis that this activity arises from crosstalk may be ruled out thanks to the characteristics of the EMG probes used, since crosstalk was always verified by using double differential probes. An explanation of the TA activity in this phase, usually not reported in healthy references, could be related to the activity of the TA as a foot inversion muscle for controlling balance during single support and contralateral limb swing.

The different modalities of activation found for GL are in agreement with Sutherland findings [10] with respect to the absence or presence of a swing-phase activity and of a premature activation during stance, which he explains in terms of mature and immature pattern of activation. The fact that in this study children over 6 years show a pattern previously considered immature in a high percentage of the subjects 2 years and younger [24], is a further confirmation of the difficulty to define a fixed threshold between mature and immature gait. Variability in children may indicate, as Granata et al. suggested [22], a stabilizing control even more responsive than in adults, supporting the hypothesis that a young neurocontrol system can operate on more degrees of freedom. Sutherland reports a controversy as to whether the plantar flexor muscles produce ankle plantar flexion and knee-flexion in pre-swing, asserting that these muscles are silent during this period [23]. Winter, on the contrary, believes that the knee flexion during this period results from plantar flexor muscle action [5]. Our results show that in 27% of strides the GL is silent during pre-swing (1-activation modality) as asserted by Sutherland [23], but also show that in 29% of strides (3-activation modality) GL is active in pre-swing, as asserted by Winter [5].

In 95% of strides (2-, 3- and 4-activation modalities considered all together) VM is active from midswing continuing to midstance as already described by Sutherland [10], although the mean duration of activity during the first part of stance is less prolonged. However, [10] describes only a single VM pattern corresponding to the 2-activation modality we found in 57% of strides. We emphasize that in 30% of strides there is also an activation in terminal stance, which could be aimed at stabilizing patella before entering pre-swing phase.

The phasic activity of RF is closely similar to that of VM from midswing up to the successive stance phase. However, the dominant pattern is characterized by a further activation before the stance to swing transition. Our results are in agreement with most of literature [2, 11, 12, 18, 23] that reports activity of RF as biphasic with a first burst of activation occurring around swing to stance transition and a second burst occurring during the stance to swing transition. On the contrary, Perry [4] and Nene et al. [25], by means of fine wires, found a monophasic pattern of activity during the stance to swing transition. Nene et al. [25] explained this disagreement with crosstalk due to the lack of selectivity of surface probes, but Annaswamy et al. [26], also working with fine wires and hence ruling out the crosstalk hypothesis, report a biphasic activity of RF. Moreover, our data show that in 25% of strides is not present any RF activity during stance to swing transition, while it is present from midswing up to the successive stance phase.

The most frequent activation modality of LH is monophasic, starting during midswing and continuing up to midstance. However, other bursts of activity are present from midstance to pre-swing that slightly anticipate (10% GC) the RF activity to control hip and knee moments when body weight is transferred on the contralateral foot. This finding is of interest as never focused before.

4.1 Limits of the present work

Notice that since only three foot-switches were used under each sole (heel, first metatarsal head, fifth metatarsal head) instead of four (heel, first metatarsal head, fifth metatarsal head, big toe) the meaning of the terms “stance” and “swing” is different from its rigorous definition.

It should be noted that some activation patterns might contain very low, just above noise, EMG activity intervals, that maybe expected to be of functionally negligible mechanical effectiveness. This eventuality has to be carefully checked during a clinical evaluation. However, if an EMG burst has a small amplitude relative to other bursts of the same muscle, from a motor control point of view that burst should not be disregarded, even if the mechanical effect of the muscle activity could be negligible.

5. Conclusions

This study was designed to build a reference frame for kinesiological EMG in school-age children, in terms of on-off muscular activity during gait cycle. Data from the present work show that different activation modalities are present even in consecutive strides of the same subject. Moreover, even in a range of age in which a mature gait should be established, our study confirms that children walk at free speed with a high variability in the patterns of muscular activation.

The statistical identification of the activation intervals and the statistical analysis performed on an exceptionally high number of strides for each participant allowed us to obtain the most recurrent frequencies of activation intervals, providing a series of quantitative information about timing of activation of five lower limb muscles in children, useful for comparison in the clinical context and as a reference for designing future gait studies.

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References

[1] Frigo C, Crenna P, Multichannel SEMG in clinical gait analysis: A review and state-of-the-art. Clin Biomech 2009; 24:236–245.

[2] Patikas D, Wolf SI, Schuster W, Armbrust P, Dreher T, Döderlein L. Electromyographic patterns in children with cerebral palsy: Do they change after surgery? Gait Posture 2007; 26(3):362–371.

[3] Romkes J, Hell AK, Brunner R, Changes in muscle activity in children with hemiplegic cerebral palsy while walking with and without ankle–foot orthoses. Gait Posture 2006; 24:467–474.

[4] Perry J. Gait analysis. Normal and pathological function. Thorofare: Slack Incorporated; 1992.

[5] Winter DA. Biomechanics and Motor Control of Human Movement, 2nd ed. New York: Wiley, 1990.

[6] Blanc Y, Balmer C, Landis T, Vingerhoets F. Temporal parameters and patterns of the foot roll over during walking: normative data for healthy adults. Gait Posture 1999; 10: 97–108.

[7] Sutherland DH. The evolution of clinical gait analysis part II – kinematics. Gait Posture 2002; 16(2):159–179.

[8] Sutherland DH. The evolution of clinical gait analysis part III – kinetics and energy assessment. Gait Posture 2005; 21:447–461.

[9] Hillman SJ, Stansfield BW, Richardson AM, Robb JE. Development of temporal and distance parameters of gait in normal children. Gait Posture 2009; 29:81–85.

[10] Sutherland DH. The development of mature gait. J Bone Joint Surg Am 1980; 62:336–353.

[11] Chang WN, Lipton JS, Tsirikos AI, Miller F. Kinesiological surface electromyography in normal children: range of normal activity and pattern analysis. J Electromyogr Kinesiol 2007; 17(4):437–445.

[12] Schwartz MH, Rozumalski A, Trost JP. The effect of walking speed on the gait of typically developing children. J Biomech 2008:1639–1650.

[13] Shiavi R, Green N, McFadyen B, Frazer M, Chen J. Normative childhood EMG gait patterns. J Orthop Res 1987; 5:283–295.

[14] Dusing SC, Thorpe DE. A normative sample of temporal and spatial parameters in children using GAITRite electronic walkway. Gait Posture 2007; 25:135–139.

[15] Bonato P, D'Alessio T, Knaflitz M. A statistical method for the measurement of muscle activation intervals from surface myoelectric signal during gait. IEEE Trans Biomed Eng 1998; 45:287–299.

[16] Balestra G, Knaflitz M, Molinari F. Principles of statistical gait analysis. Proceedings of XIV ISEK Conference; 2002.

[17] Staude G, Flachenecker C, Daumer M, Wolf W. Onset detection in surface electromyographic signals: a systematic comparison of methods. EURASIP J Appl Signal Processing 2001; 2: 67–81.

[18] Winter DA. The Biomechanics and Motor Control of Human Gait: Normal, Elderly and Pathological, 2nd ed. Waterloo Biomechanics, 1991.

[19] Kadaba M, Ramakrishnan HK, Wootten ME. Gainey J, Gorton G, Cochran GV, Repeatability of kinematic, kinetic, and electromyographic data in normal adult gait, J Orthop Res 1989; 6:849–860.

[20] Shiavi R, Bugle HJ, Limbird T. Electromyographic gait assessment, Part I: Adult EMG profiles and walking speed. J Rehabil Res Dev 1987; 24:13–23.

[21] Stansfield BW, Hillman SJ, Hazlewood ME, Lawson AM, Mann AM, Loudon IR, Robb JE, Normalisation of gait data in children, Gait Posture 2003; 17:81–87.

[22] Granata KP, Padua DA, Abel MF. Repeatability of surface EMG during gait in children. Gait Posture 2005; 22(4):346–350.

[23] Sutherland DH. The evolution of clinical gait analysis part l: kinesiological EMG. Gait and Posture 2001; 14:61–70.

[24] Sutherland DH. The development of mature gait. Gait Posture 1997; 6:163–170.

[25] Nene A, Byrne C, Hermens H. Is rectus femoris really a part of quadriceps? Assessment of rectus femoris function during gait in able-bodied adults. Gait Posture 2004; 20:1–13.

[26] Annaswamy TM, Giddings CJ, Della Croce U, Kerrigan DC. Rectus Femoris: Its Role in Normal Gait. Arch Phys Med Rehabil 1999; 80(8):930–934.

Table 1

Description of the population of 100 children investigated in this study.

Age groups (years)	N	Gender (M/F)	Age (months)	Height (cm)	Weight (kg)	Cadence (steps/min)	Velocity/√(Height×g) (dimensionless)
6-7	10	7/3	80.3 ± 2.1	122.2 ± 7.1	24.2 ± 5.8	125.5 ± 8.3	0.28 ± 0.03
7-8	19	6/13	90.7 ± 3.7	126.3 ± 6.9	27.1 ± 5.3	123.5 ± 9.0	0.29 ± 0.04
8-9	22	12/10	102.9 ± 2.9	130.4 ± 5.5	28.8 ± 4.1	121.2 ± 12.1	0.27 ± 0.04
9-10	22	11/11	115.4 ± 3.2	138.7 ± 7.7	34.5 ± 7.8	116.1 ± 10.5	0.29 ± 0.06
10-11.5	27	15/12	127.4 ± 4.6	140.8 ± 5.9	34.0 ± 5.0	110.1 ± 7.1	0.27 ± 0.03

Values of Age, Height, Weight, Cadence and Normalized Velocity are reported as mean ± 1 standard deviation. g is the acceleration due to gravity equal to 9.81 m/s^2.

Table 2

Muscle activation intervals. Activation onset and offset of each muscle are reported when 1, 2, 3, 4 or 5 activations are present during the gait cycle. The occurrence of each modality is displayed in the second column. Mean value over the population, standard deviation (SD) and Confidence Interval (CI) at 95 % are reported separately for the left and the right side.

		TIBIALIS ANTERIOR							
Num activ.	Relative frequency of each modality	Left side				Right side			
		ONSET (% of gait cycle)		OFFSET (% of gait cycle)		ONSET (% of gait cycle)		OFFSET (% of gait cycle)	
		Mean	CI	Mean (SD)	CI	Mean	CI	Mean	CI
1	0.9 %	48.4(25.3)	38.1 - 58.8	72.5(31.9)	59.4 - 85.5	41.5(30.9)	26.8 - 56.1	87.1(27.0)	74.3 - 99.9
2	23.1 %	2.1(4.8)	0.21 - 4.1	13.7(8.4)	10.3 - 17.1	2.1(5.1)	-0.3 - 4.5	15.8(13.1)	9.6 - 22.0
		61.1(10.7)	56.7 - 65.5	98.6(3.2)	97.3 - 99.9	60.0(8.2)	56.1 - 63.9	99.1(2.0)	98.1 - 100.1
3	47.6 %	0.1(0.4)	-0.01 - 0.3	8.9(4.7)	7.0 - 10.9	0.2(0.5)	-0.1 - 0.4	9.7(4.1)	7.8 - 11.6
		48.8(7.7)	45.6 - 51.9	65.0(9.0)	61.4 - 68.7	48.7(7.3)	45.2 - 52.2	65.5(8.7)	61.4 - 69.7
		79.4(8.5)	75.9 - 82.9	99.8(0.6)	99.5 - 100.0	78.6(8.5)	74.6 - 82.7	99.8(0.4)	99.6 - 100.0
4	23.2 %	0.0(0.2)	-0.1 - 0.1	7.5(3.6)	6.0 - 9.0	0.0(0.2)	-0.1 - 0.1	7.8(3.0)	6.4 - 9.2
		29.9(8.5)	26.5 - 33.4	39.7(9.1)	36.0 - 43.4	29.1(7.2)	25.7 - 32.6	38.6(7.8)	34.9 - 42.3
		57.9(6.2)	55.3 - 60.4	73.8(6.2)	71.3 - 76.4	57.2(5.5)	54.6 - 59.8	73.3(6.4)	70.3 - 76.4
		83.9(5.9)	81.4 - 86.3	99.9(0.6)	99.6 - 100.1	83.3(5.6)	80.6 - 85.9	99.9(0.3)	99.8 - 100.0
5	5.1 %	0.0(0.0)	0.0 - 0.0	6.2(3.4)	4.8 - 7.6	0.0(0.1)	-0.0 - 0.0	6.4(3.1)	5.0 - 7.9
		19.4(8.7)	15.9 - 23.0	27.5(9.9)	23.4 - 31.5	19.5(9.4)	15.0 - 24.0	27.0(10.0)	22.3 - 31.8
		43.2(10.3)	39.0 - 47.4	52.5(11.9)	47.6 - 57.3	42.9(10.6)	37.9 - 48.0	52.5(12.0)	46.8 - 58.2
		63.9(7.4)	60.9 - 67.0	77.1(5.4)	74.9 - 79.3	63.2(9.1)	58.9 - 67.5	77.2(7.1)	73.8 - 80.6
		86.4(5.4)	84.1 - 88.6	100.0(0.2)	99.9 - 100.0	85.7(6.4)	82.6 - 88.7	99.9(0.4)	99.7 - 100.1
		GASTROCNEMIUS LATERALIS							
1	26.5 %	13.7(8.1)	12.1 - 15.3	49.9(7.1)	48.5 - 51.3	14.5(8.0)	12.9 - 16.2	49.5(6.4)	48.3 - 50.8
2	34.3 %	7.5(4.4)	6.6 - 8.3	37.5(7.3)	36.1 - 39.0	7.2(4.5)	6.3 - 8.1	36.8(7.4)	35.3 - 38.3
		67.0(11.9)	64.6 - 69.3	79.5(10.3)	77.5 - 81.6	66.7(11.9)	64.3 - 69.1	80.5(9.6)	78.5 - 82.4
3	28.6 %	3.2(3.2)	2.6 - 3.8	22.0(9.8)	20.0 - 23.9	2.4(3.1)	1.8 - 3.0	18.8(10.2)	16.7 - 20.8
		34.2(9.3)	32.3 - 36.1	55.3(7.0)	53.9 - 56.7	31.3(9.9)	29.3 - 33.3	55.3(6.2)	54.0 - 56.6
		86.7(9.3)	84.9 - 88.6	93.8(7.6)	92.3 - 95.3	87.8(7.0)	86.4 - 89.2	95.1(6.1)	93.9 - 96.4
4	9.4 %	1.5(3.1)	0.9 - 2.1	12.1(9.9)	10.1 - 14.1	1.1(2.4)	0.6 - 1.6	10.7(10.3)	8.6 - 12.7
		22.2(10.0)	20.2 - 24.2	46.3(9.8)	44.3 - 48.2	20.7(9.8)	18.7 - 22.6	45.4(8.9)	43.6 - 47.2
		58.0(11.9)	55.6 - 60.3	68.4(8.9)	66.6 - 70.2	58.0(10.8)	55.9 - 60.2	68.5(7.8)	66.9 - 70.1
		92.0(6.5)	90.7 - 93.2	97.9(5.6)	96.8 - 99.1	92.3(4.5)	91.4 - 93.2	98.4(3.5)	97.7 - 99.1
5	1.2 %	0.3(1.6)	-0.0 - 0.6	5.0(4.7)	4.1 - 6.0	0.7(2.6)	0.2 - 1.2	8.1(10.7)	6.0 - 10.3
		16.5(7.5)	15.0 - 18.0	36.1(13.7)	33.3 - 38.8	15.8(10.5)	13.7 - 17.9	37.2(14.3)	34.3 - 40.0
		43.4(15.1)	40.4 - 46.4	58.2(8.8)	56.4 - 59.9	44.6(14.6)	41.6 - 47.5	57.5(9.3)	55.6 - 59.4
		69.7(10.0)	67.7 - 71.7	76.7(9.2)	74.9 - 78.6	71.5(11.2)	69.3 - 73.8	78.4(9.9)	76.4 - 80.4
		93.2(3.6)	92.5 - 93.9	99.7(1.2)	99.4 - 99.9	93.9(4.1)	93.1 - 94.7	100.0(0.1)	100.0 - 100.0
		VASTUS MEDIALIS							
1	4.2 %	26.0(23.8)	16.7 - 35.4	44.6(23.2)	35.5 - 53.7	33.1(35.3)	20.2 - 45.9	63.0(34.9)	50.3 - 75.6
2	56.7 %	0.5(1.6)	-0.1 - 1.1	19.6(8.6)	16.2 - 22.9	0.6(2.0)	-0.1 - 1.3	19.6(8.6)	16.5 - 22.8
		83.9(4.7)	82.0 - 85.7	98.4(4.7)	96.6 - 100.2	83.5(5.8)	81.4 - 85.7	99.2(3.1)	98.0 - 100.3
3	29.8 %	0.1(0.6)	-0.1 - 0.4	16.5(6.5)	14.0 - 19.0	0.1(0.5)	-0.1 - 0.3	16.6(5.1)	14.7 - 18.4
		38.1(9.7)	34.3 - 41.9	46.0(10.0)	42.0 - 49.9	39.7(9.3)	36.4 - 43.1	48.2(9.7)	44.7 - 51.7
		84.8(4.2)	83.2 - 86.5	99.4(2.3)	98.5 - 100.3	84.3(4.5)	82.7 - 85.9	99.9(0.7)	99.6 - 100.1
4	8.1 %	0.2(0.6)	-0.1 - 0.4	15.8(5.7)	13.6 - 18.0	0.1(0.3)	-0.1 - 0.2	15.1(5.2)	13.2 - 17.0
		28.4(8.5)	25.1 - 31.8	36.0(8.5)	32.6 - 39.3	26.4(6.5)	24.1 - 28.8	34.1(7.0)	31.6 - 36.7
		51.3(11.4)	46.9 - 55.8	58.3(11.1)	53.9 - 62.6	49.7(9.9)	46.0 - 53.3	56.5(10.1)	52.8 - 60.1
		85.1(5.5)	83.0 - 87.3	99.6(3.0)	98.4 - 100.7	84.2(5.0)	82.4 - 86.0	100.0(0.4)	99.8 - 100.1
5	1.2 %	0.0(0.0)	0.0 - 0.0	15.7(7.2)	12.9 - 18.5	0.0(0.0)	0.0 - 0.0	13.9(5.9)	11.7 - 16.0
		23.8(10.3)	19.8 - 27.8	30.2(10.6)	26.1 - 34.4	22.5(8.6)	19.3 - 25.6	29.8(9.1)	26.5 - 33.2
		38.0(12.6)	33.0 - 42.9	44.8(13.6)	39.5 - 50.1	39.3(9.2)	36.0 - 42.6	45.1(9.5)	41.7 - 48.6
		57.0(16.3)	50.6 - 63.4	62.8(16.0)	56.5 - 69.0	57.6(13.3)	52.8 - 62.4	64.0(13.2)	59.3 - 68.8
		86.4(7.1)	83.6 - 89.2	100.0(0.0)	100.0 - 100.0	84.2(6.4)	81.9 - 86.5	99.9(0.6)	99.7 - 100.1

Num activ.	Relative frequency of each modality	Left side				Right side			
		ONSET (% of gait cycle)		OFFSET (% of gait cycle)		ONSET (% of gait cycle)		OFFSET (% of gait cycle)	
		Mean	CI	Mean	CI	Mean	CI	Mean	CI
		RECTUS FEMORIS							
1	5.5 %	19.3(20.5)	13.0 - 25.7	44.7(27.6)	36.1 - 53.3	23.7(25.0)	15.8 - 31.5	53.2(31.0)	43.5 - 62.9
2	24.8 %	2.5(6.4)	0.5 - 4.5	21.5(9.2)	18.7 - 24.4	2.1(5.0)	0.6 - 3.7	22.1(9.0)	19.3 - 25.0
		76.2(14.0)	71.9 - 80.6	95.8(9.0)	93.0 - 98.6	77.8(13.8)	73.5 - 82.1	98.0(4.9)	96.5 - 99.6
3	48.4 %	0.7(2.9)	-0.2 - 1.6	18.0(5.8)	16.2 - 19.8	0.4(1.8)	-0.1 - 1.0	17.8(5.7)	16.0 - 19.6
		46.1(5.6)	44.4 - 47.8	58.9(7.1)	56.7 - 61.1	46.7(5.6)	44.9 - 48.4	59.5(6.7)	57.4 - 61.6
		85.0(5.4)	83.4 - 86.7	98.3(5.6)	96.6 - 100.0	85.2(4.6)	83.8 - 86.7	99.4(2.2)	98.8 - 100.1
4	17.8 %	0.3(1.8)	-0.2 - 0.9	16.2(5.6)	14.4 - 17.9	0.3(1.5)	-0.2 - 0.8	16.2(5.1)	14.6 - 17.8
		35.0(6.8)	32.9 - 37.1	42.9(7.0)	40.8 - 45.1	34.2(6.4)	32.2 - 36.2	42.1(6.6)	40.1 - 44.2
		57.4(6.4)	55.4 - 59.3	67.6(6.0)	65.7 - 69.4	56.1(5.8)	54.3 - 57.9	66.6(5.7)	64.8 - 68.4
		86.8(4.6)	85.4 - 88.3	99.7(1.6)	99.2 - 100.2	86.3(3.7)	85.2 - 87.5	99.7(1.1)	99.4 - 100.1
5	3.6 %	0.1(0.3)	-0.1 - 0.2	14.9(6.7)	12.9 - 17.0	0.0(0.0)	0.0 - 0.0	15.5(6.6)	13.4 - 17.6
		27.1(8.8)	24.4 - 29.8	33.4(9.0)	30.6 - 36.2	26.8(8.2)	24.2 - 29.4	33.2(7.8)	30.8 - 35.7
		45.2(7.9)	42.8 - 47.6	52.6(8.7)	49.9 - 55.3	46.0(7.4)	43.7 - 48.3	54.3(9.2)	51.4 - 57.2
		62.2(8.3)	59.6 - 64.8	70.9(7.8)	68.5 - 73.4	64.0(10.5)	60.7 - 67.3	71.5(9.2)	68.6 - 74.4
		86.3(4.8)	84.8 - 87.8	99.9(0.9)	99.6 - 100.2	86.6(5.7)	84.8 - 88.3	99.8(1.9)	99.2 - 100.4
		LATERAL HAMSTRINGS							
1	5.0 %	50.7(32.0)	41.1 - 60.2	85.7(20.6)	79.6 - 91.9	59.2(27.7)	50.6 - 67.8	85.4(19.7)	79.3 - 91.5
2	46.9 %	2.8(5.4)	1.2 - 4.4	28.1(10.4)	25.0 - 31.2	3.3(5.9)	1.5 - 5.1	26.8(9.5)	23.8 - 29.7
		77.6(4.6)	76.2 - 79.0	97.9(5.6)	96.2 - 99.5	77.4(4.2)	76.1 - 78.7	98.6(3.4)	97.5 - 99.6
3	35.7 %	0.9(2.1)	0.3 - 1.5	17.2(7.4)	15.0 - 19.4	1.3(2.9)	0.3 - 2.2	16.2(6.5)	14.2 - 18.2
		35.2(9.9)	32.2 - 38.2	47.4(8.3)	45.0 - 49.9	35.9(9.9)	32.8 - 38.9	48.4(8.3)	45.8 - 51.0
		79.8(3.9)	78.6 - 80.9	99.2(2.3)	98.5 - 99.9	79.4(3.5)	78.3 - 80.5	99.3(1.9)	98.7 - 99.8
4	10.5 %	0.4(1.4)	-0.0 - 0.8	12.3(7.2)	10.1 - 14.4	0.3(0.8)	0.0 - 0.5	12.1(7.1)	9.9 - 14.3
		24.0(8.6)	21.5 - 26.6	34.7(7.6)	32.5 - 37.0	24.4(9.3)	21.5 - 27.3	35.9(8.6)	33.2 - 38.6
		51.0(11.1)	47.7 - 54.3	58.9(11.1)	55.6 - 62.2	52.4(9.3)	49.5 - 55.3	61.2(9.1)	58.4 - 64.0
		80.6(5.9)	78.9 - 82.4	99.1(3.9)	98.0 - 100.3	80.7(4.8)	79.2 - 82.2	99.5(1.3)	99.1 - 99.9
5	1.9 %	0.1(0.7)	-0.1 - 0.3	8.4(5.0)	6.9 - 9.9	0.3(1.3)	-0.1 - 0.7	10.6(7.1)	8.4 - 12.8
		17.8(6.3)	15.9 - 19.7	28.3(8.9)	25.7 - 31.0	20.2(9.0)	17.5 - 23.0	30.4(8.9)	27.6 - 33.1
		39.8(9.8)	36.9 - 42.8	46.9(8.7)	44.3 - 49.5	42.1(10.8)	38.8 - 45.4	50.3(9.8)	47.3 - 53.4
		61.1(10.0)	58.1 - 64.1	67.8(10.3)	64.7 - 70.9	63.5(10.2)	60.4 - 66.7	71.0(11.3)	67.5 - 74.5
		82.0(5.7)	80.3 - 83.7	99.7(0.9)	99.5 - 100.0	83.1(7.1)	80.9 - 85.3	99.7(1.1)	99.4 - 100.0

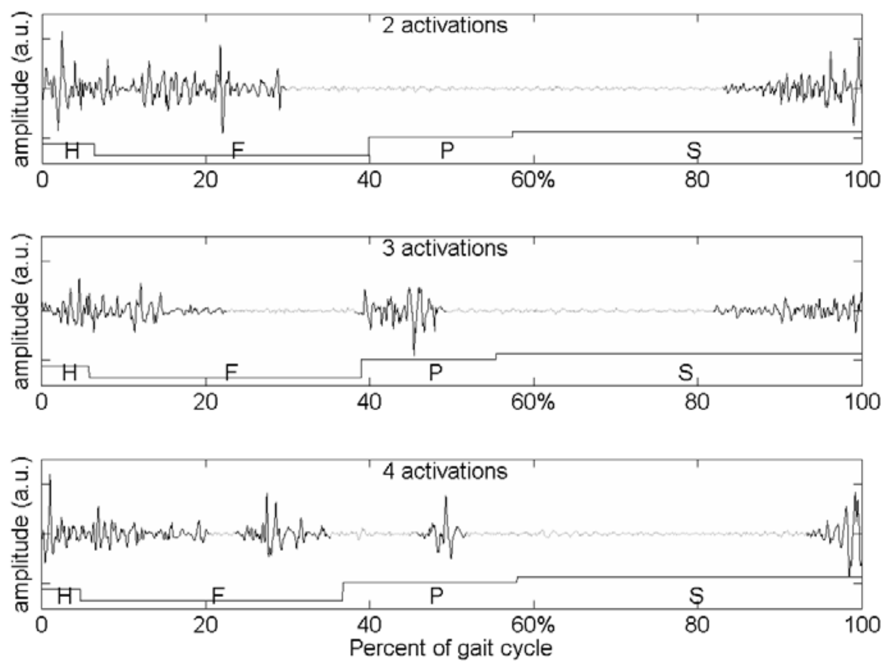
Figure captions

Fig. 1. An example of EMG signal of RF muscle showing 2 activations, 3 activations and 4 activations. The signals have been extracted from different strides of the same subject, during the same walk. The 4-level foot-switch signals are shown superimposed as a reference of the correspondent H-F-P-S gait phases.

Fig. 2. Different occurrences of EMG activation patterns during the walk of a specific child. For each muscle, it is shown the percentage frequency of five different modalities with 1, 2, 3, 4 and 5 activations, respectively.

Fig. 3. Horizontal bars are grey-level coded; black: condition observed for all children, white: condition never met. a) Foot contact timing over the population (4-level signal): H = heel contact; F = Flat foot contact; P = Push off; S = Swing. Muscle activation onset and offset instants over the population for b) TA, c) GL, d) VM, e) RF and f) LH, as % of gait cycle, for five different modalities with 1, 2, 3, 4 and 5 activations, respectively. On the right-hand side of each plot: percentage frequency of each modality. The H, F, P, S phases are shown superimposed, delimited by dashed vertical lines.

Figure 1



2 activations
3 activations
4 activations
amplitude (a.u.)
H
F
P
S
0
20
40
60%
80
100
Percent of gait cycle

Figure 2

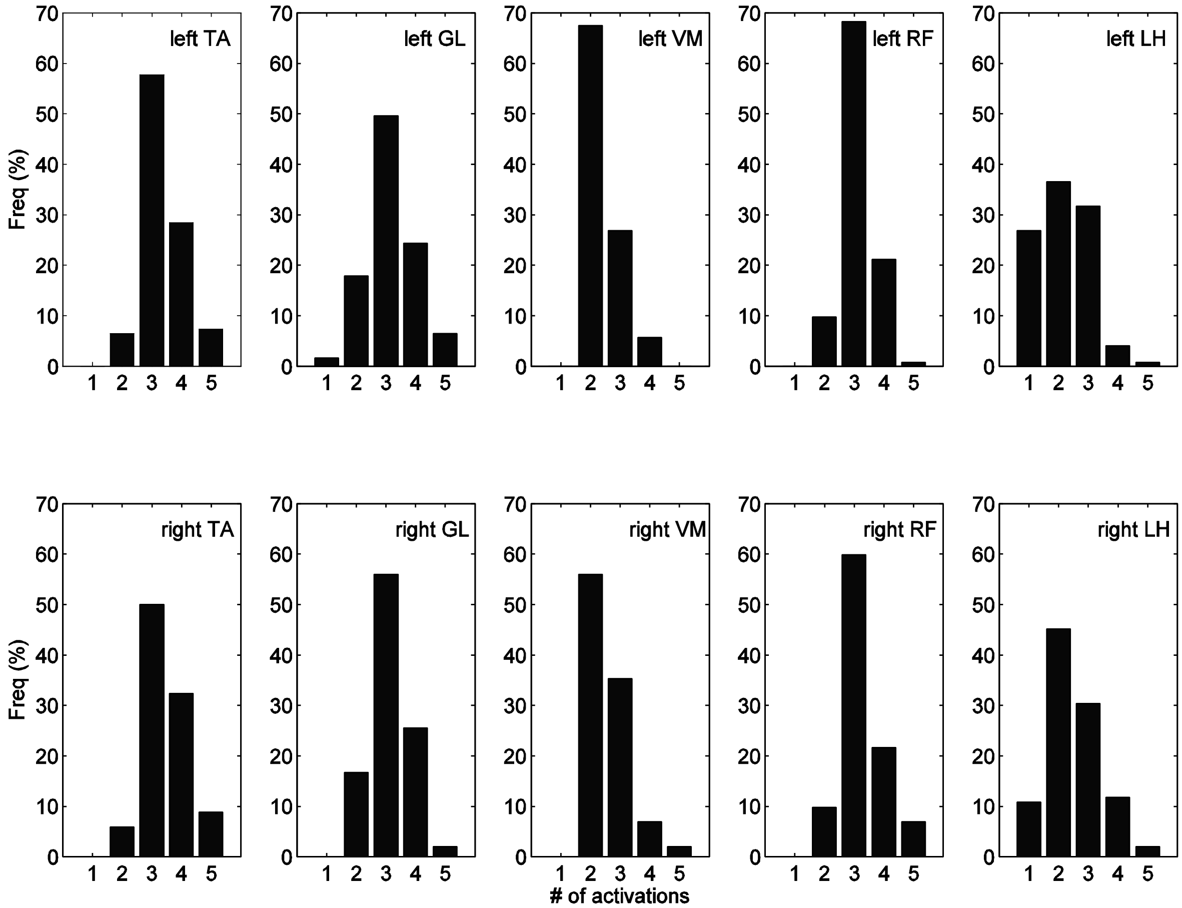
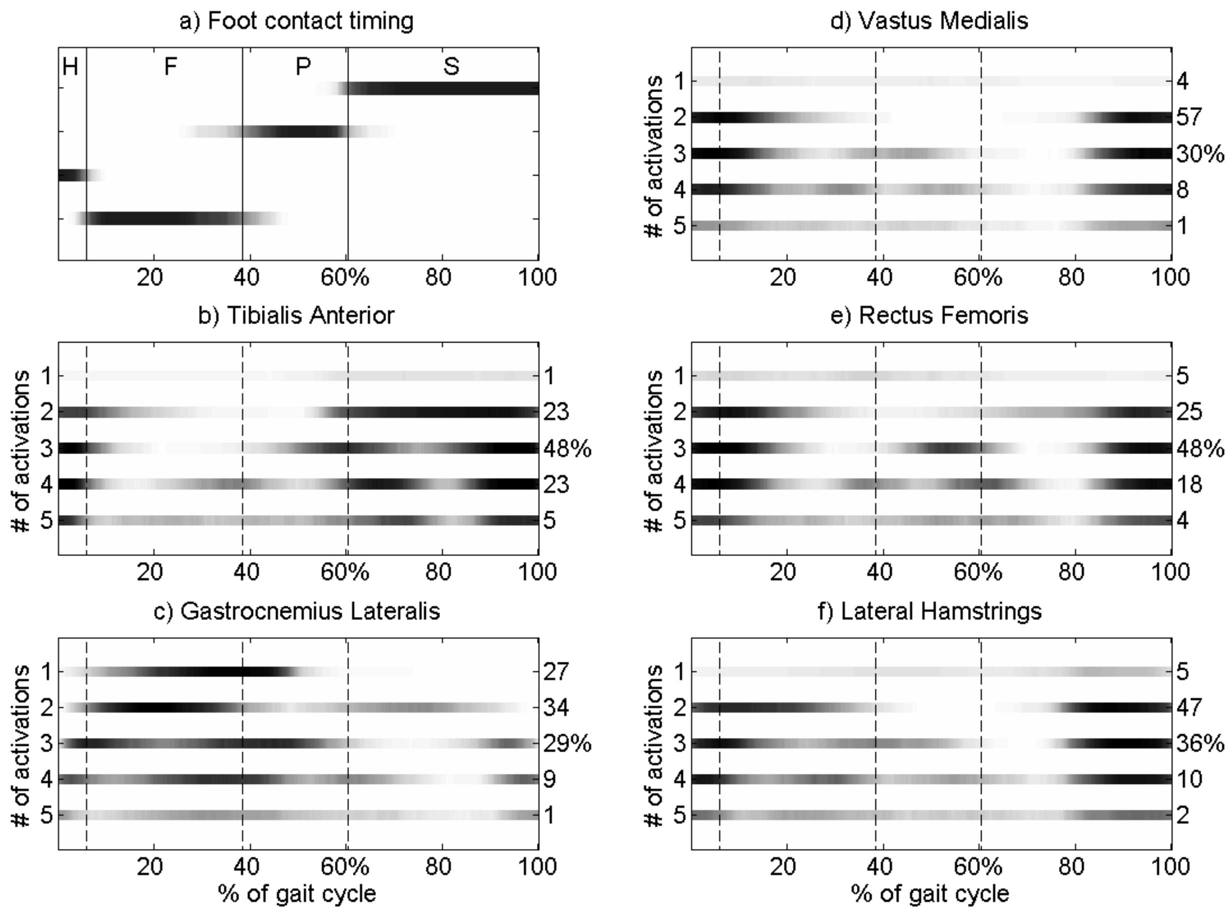

left TA
left GL
left VM
left RF
left LH
right TA
right GL
right VM
right RF
right LH
Freq (%)
# of activations

Figure 3



a) Foot contact timing
H
F
P
S
20
40
60%
80
100
d) Vastus Medialis
# of activations
1
2
3
4
5
4
57
30%
8
1
b) Tibialis Anterior
1
23
48%
23
5
e) Rectus Femoris
5
25
48%
18
4
c) Gastrocnemius Lateralis
27
34
29%
9
1
% of gait cycle
f) Lateral Hamstrings
5
47
36%
10
2
% of gait cycle