

# Gait analysis on force treadmill in children: comparison with results from ground-based force platforms

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Gait analysis (GA) typically includes surface electromyographic (sEMG) recording from several lower limb muscles, optoelectronic measurement of joint rotations, and force recordings from ground-based platforms. From the latter two variables, the muscle power acting on the lower limb joints can be estimated. Recently, gait analysis on a split-belt force treadmill (GAFT) was validated for the study of adult walking. It showed high reliability of spatiotemporal, kinematic, dynamic, and sEMG parameters, matching those obtainable with GA on the basis of ground walking. GAFT, however, still needs validation in children. Potential differences with respect to adult GAFT relate to (a) possible high signal-to-noise ratio, given the lower forces applied; (b) higher differences between treadmill and over-ground walking; and (c) limited compliance with the experimental setup. This study aims at investigating whether GAFT provides results comparable with those obtainable from ground walking in children and consistent with results from GAFT in adults. GAFT was applied to three groups of healthy children aged 5–6 years ( $n = 6$ ), 7–8 years ( $n = 6$ ), and 9–13 years ( $n = 8$ ) walking at the same average speed spontaneously adopted overground. The results were compared with those obtained from another study applying GA to an age-matched and speed-matched sample of 47 children, and with those obtained from GAFT in adults. The reliability (as indicated by the SD) of both spatiotemporal and dynamic parameters was higher in GAFT compared with GA. In the 5–6-, 7–8-, and 9–13-year-old groups, at average speeds of 0.83, 1.08, and 1.08 m/s, step length was shorter by 9.19, 3.57, and 2.30% compared with GA in controls at comparable speeds,

respectively. For the youngest group, a lower power generation from the plantar flexors (peak power:  $1.35 \pm 0.32$  vs.  $2.11 \pm 1.02$  W/kg) and a slightly more flexed posture of the hip, knee, and ankle joints were observed during GAFT compared with GA in controls. The other gait parameters were very similar between the GAFT and the GA groups. The shortening of step length during GAFT, relative to GA at superimposable speed, was on average of all children 6.8%, in line with the 8% decrease found in adults. The profiles of sEMG and joint rotations, and all of the weight-standardized joint power parameters, matched those recorded in adults. The entire experimental session lasted about 1 h. All children complied with the experimental setting and easily completed the requested tests. In conclusion, GAFT seems to be a promising alternative to conventional GA in children. *International Journal of Rehabilitation Research* 40:315–324 Copyright © 2017 The Author(s). Published by Wolters Kluwer Health, Inc.

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## Introduction

Gait analysis (GA) in children is usually performed during over-ground walking (GW), with ground reaction forces being recorded through force platforms embedded in the floor. Body kinematics and surface electromyography (sEMG) are recorded simultaneously.

Gait analysis on force treadmills (GAFT, i.e. with treadmills resting on force sensors) was introduced in 2008. The

method has several advantages with respect to over-ground GA: the average speed is known and constant, thus increasing the test reliability, it allows to record several successive strides in a few seconds, and little room is needed (Tesio and Rota, 2008).

The potential disadvantages relate to the quality of force recordings on a long and vibrating belt (hence, to the potentially lower accuracy, reliability, and dynamic sensitivity of the force records), the unusual sensory context (moving body within a visually stable surround), and the need for a dedicated expensive treadmill.

Substantial equivalence between the kinematics of walking on ground and on treadmill has already been reported in the

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literature for healthy adults (Riley *et al.*, 2007). In a previous paper (Tesio and Rota, 2008), it was shown that the signal-to-noise ratio was acceptably low. Also, despite an 8% shorter step (and thus a 8% higher cadence) adopted during treadmill walking (TW) compared with GW, for the same walking speed, the step length difference had no meaningful impact on dynamic (i.e. joint torques), ergometric (i.e. motion of the body center of mass), and neurophysiologic (lower limb sEMG patterns) variables (Lee and Hidler, 2008; Tesio and Rota, 2008).

GAFT, however, still needs validation in children. First, given the lower forces involved, compared with adult gait, the signal-to-noise ratio might become unacceptably high. Second, the mild behavioral changes (ultimately, an 8% step shortening) observed in adults might be more relevant in children. Finally, confirmation is needed for the compliance of children with respect to the GAFT setup.

In the present study, the results from GAFT on children between 5 and 13 years of age were compared with reference data already available from a sample of the same age walking on ground-based force platforms.

## Participants and methods

### Participants

#### Experimental sample

GAFT provides very reliable results because of the imposed speed, so that a sample of five to seven participants, providing six strides per each walking speed, proved to be of satisfactory size in adults (Tesio *et al.*, 2017). In this work, a sample of 20 children, with a minimum of six children per age group, was deemed sufficiently large. Healthy children were screened to participate in the study. They were daughters/sons or nieces/nephews of the staff or school-mates or friends of other recruited children. Following suggestions from the literature (Chester *et al.*, 2006), three groups were created on the basis of the following cutoff ages (years): 5–6 ( $n=6$ ); 7–8 ( $n=6$ ); and 9–13 ( $n=8$ ).

#### Control sample for spatiotemporal, kinematic, and dynamic variables

The results were compared with a reference control sample from a previous study of another author (Chester *et al.*, 2006), who kindly provided the original data matrix. This sample included 47 healthy children walking on a floor-mounted platform at spontaneous average speed and cadence. Participants were grouped according to the following age classification (years): 3–4 ( $n=13$ ); 5–6 ( $n=10$ ); 7–8 ( $n=13$ ); and 9–13 ( $n=12$ ). No sEMG data were available from this study.

#### Control sample for surface electromyographic data

An age-related profile of sEMG waveforms of the lower limbs during walking could not be retrieved from the literature. However, the on–off sEMG timing recorded during GW was available from another previous study

(Agostini *et al.*, 2010). The authors provided the prevalence of various on–off patterns recorded within their sample (100 participants, 6–11 years). The on–off pattern closest to the one observed for each age class during TW in the present study was then represented as a series of interrupted horizontal segments synchronized with the experimental sEMG tracings (see the Results section).

### Ethics

For the experimental group, parental consent and child assent were obtained before participation in the study. Parents voluntarily completed a questionnaire designed to identify clinical conditions that could affect their child's walking skills. Children had to be free from neurologic and/or orthopedic impairments that could affect walking skills. The study was approved by the ethical committee of the Istituto Auxologico Italiano, IRCCS, Milan, Italy (statement CE 30-5-2006).

### Walking test

A walking test on ground was performed before GA as described previously (Rota *et al.*, 2011). Briefly, children were asked to walk a distance of 10 m along a 24 m long corridor at their preferred speed for four times in opposite directions. During each of the 10 m walks, one operator measured time in seconds using a stopwatch; meanwhile, steps were counted visually by another operator. From distance, time, and step count measures, the average walking speed ( $10\text{ m} \times \text{time}^{-1}$ ), step length ( $10\text{ m} \times \text{step count}^{-1}$ ), and step cadence ( $\text{step count} \times \text{time}^{-1}$ ) were obtained. The mean values among the four walking bouts were computed and considered for further analysis. The mother or another relative of the tested child was always present in the laboratory.

### Instrumentation

The methods to record joint kinematics and dynamics and sEMG during walking have been described previously in detail (Tesio and Rota, 2008). Briefly, gait was analyzed using a force-mounted split-belt treadmill (model ADAL 3D; Medical-Development, Andrézieux-Bouthéon, France). The treadmill consists of two parallel, independent, half-treadmills. Each half-treadmill is 1.26 m long and 0.3 m large, and it is mounted on four 3D piezoelectric force sensors (KI 9048B; Kistler, Winterthur, Switzerland). Speed can be regulated in 0.1 m/s. Force and speed signals were sampled at 250 Hz. In this study, the two half-treadmills ran at the same speed, and force signals from both sides were summed vectorially, thus reproducing the signals generated from a single, large treadmill.

### Experimental protocol

Participants had to wear a t-shirt, short pants, and light gym shoes. Leg length was also measured bilaterally while standing and taken as the distance from the anterior–superior iliac spine to the midpoint between the internal and the external malleolus.

Reflective skin markers were attached to the body landmark as per the Davis anthropometric model (Davis *et al.*, 1991). The 3D displacement of the markers was captured by 10 near-infrared stroboscopic cameras (sampling rate 250 Hz, Smart-D optoelectronic system; BTS Bioengineering Spa, Milan, Italy) placed on the walls around the treadmill, thus enabling the estimation of ankle, knee, and hip joint rotations.

The sEMG probes (FreeEMG; BTS Bioengineering Spa) were positioned, bilaterally on the skin covering the bellies of biceps femoris, rectus femoris, vastus medialis, gastrocnemius medialis, tibialis anterior, as per SENIAM guidelines (Hermens *et al.*, 1999). The sample frequency was set at 1 kHz. The overall weight of the on body equipment was 180 g.

Once equipped, participants' height and weight were measured (accuracy 2 mm and 50 g, respectively). Then, the participant was requested to stand quietly on the treadmill for about 15 s, thus allowing for the vertical force calibration of the participant's mass. Then, he/she was allowed to adapt to TW for about 30 s. As a cautionary measure, the examiner supplied a hand to the tested participant during the speed-increasing phases to provide a safe adaptation to the new walking condition.

During the experimental trial, the participant was asked to walk at increasing average speeds, in 0.1 m/s increments, up to each participant's floor spontaneous speed. The goal was to analyze six subsequent strides with no visible changes in speed or any episode of stumbling or imbalance (Tesio and Rota, 2008). The participant was warned before each speed change, which took 5 s in a ramp-like manner. The entire testing session, inclusive of participants' dressing, device fitting, and walking, lasted for about 1 h.

## Computations

### Basic algorithms

Force signals were recorded during patients' walking for at least two entire steps on force platforms. Then, they were synchronized in space and in time with joint excursions, thus enabling computation of joint moments. During swing, torque and power at the lower limb joints were only estimated through inverse dynamics according to anthropometric modeling of body segments (Cappozzo *et al.*, 2005; Tesio and Rota, 2008).

Joint power was computed as the product of moment and joint rotation speed. As it is customary in physiology, power is defined as generated or positive when joint moment and rotation speed share the same direction (agonist muscles are contracting while shortening, thus providing 'positive' work) and as absorbed or negative otherwise.

Only those tests were considered acceptable in which the participant moved at a constant average speed (steady

state) across the platform without an appreciable drift during the period of the analysis. This requirement was considered fulfilled when the difference between the sum of the increases and the sum of the decreases in speed was within 5% of the sum of the increases in speed in both the forward and the vertical directions for one stride (Cavagna *et al.*, 1983b).

The sEMG signals were off-line rectified (time constant 0.08 s) and filtered (band pass filter 10–450 Hz).

### Spatiotemporal gait parameters

A step was defined as the ensemble of kinematic, dynamic, and electrophysiologic events taking place between two subsequent foot–ground contacts. Foot–ground contact phases were determined from vertical forces exceeding 9 N [a threshold above the background noise (Tesio and Rota, 2008)]. The sequence of two consecutive steps has been named a stride. Step length was defined as the sagittal distance between the lateral malleolus of the posterior and of the anterior foot, respectively, at the ground strike of the anterior foot (so-called 'posterior step'). Step time was defined as the time between the initial heel–ground contact of one foot and the initial heel–ground contact of the opposite foot. The side of the step and the corresponding length and time were named after the posterior foot during double stance. This is at variance with the convention adopted most frequently. However, it has the advantage of relating the step length and time (and the related kinematics) to step dynamics, that is, to the propulsion provided by the posterior leg (Tesio *et al.*, 2017).

### Data analysis

All signals were synchronized and analyzed off-line through algorithms available within the SMART Software Suite (BTS Bioengineering Spa). Stride time was normalized to 100 time points. Results were inspected visually for gross artifacts (e.g. because of stumbling) and averaged across six subsequent strides within each participant, and then grand-averaged across participants, irrespective of the beginning step. In fact, in healthy participants, the mechanics of gait is fully reproducible between subsequent steps (Cavagna *et al.*, 1983b). Further computations, statistics, and graphic representation were performed using MATLAB (version 8; MathWorks Inc., Natick, Massachusetts, USA), STATA (version 14.0; STATA Corp., College Station, Texas, USA), and SigmaPlot (version 10.0; Systat Software Inc., San Jose, California, USA) software.

### Statistics

Significance was set at  $P$  value less than 0.05. Age, height, and weight were compared, within each age group, using a  $t$ -test (unpaired, unequal variances) with Bonferroni's correction for multiplicity. The comparison of spatio-temporal gait variables between the experimental and the control sample, both walking on ground, and the experimental sample walking on treadmill was also made

using a *t*-test with Bonferroni's correction. Hip, knee, and ankle joint rotation range and single-stance time (as a percent of stride time) were analyzed statistically. Within the experimental sample, an analysis of variance was carried out to test for significant differences in these variables across age classes, lower limb sides, and the (age class  $\times$  limb side) interaction. Tukey's post-hoc analyses were carried out on paired comparisons. The comparison of the experimental group walking on treadmill with the control sample walking on ground was left to the graphic superimposition of the curves (mean  $\pm$  SD bands) representing kinematic and dynamic variables of the lower limbs (Tesio and Rota, 2008; Tesio *et al.*, 2017).

## Results

### Participants

No children were excluded from the study because of denial of consent. Demographic information of the participants considered in the present study is presented in Table 1.

### Compliance of the children

The compliance of the children was excellent. They all expressed curiosity. The majority of the children performed the test as a game or as an enjoyable challenge.

### Group comparison of demographic, anthropometric, and spatiotemporal gait variables

Table 1 presents the demographic and anthropometric variables of the experimental and the control participants, divided into three age groups.

Table 2 enables a comparison of spatiotemporal gait parameters between the experimental and the control groups.

In the experimental group, no significant differences emerged for joint rotation range and standardized stance time with respect to step side. This allowed the mechanical data from both sides to be averaged.

To compare the present with the control study, each participant from the study sample was analyzed at the speed nearest to that of the corresponding age group in the reference control sample. Tables 1 and 2 show that

the experimental and the control samples were comparable with respect to the variables analyzed during GW for all age classes. When TW and GW in the controls were compared, the duration of the stance phase seemed to be slightly higher in controls at all ages. In any case, all results are in line with those from previous studies on children (Sutherland *et al.*, 1980; Cavagna *et al.*, 1983a).

Figure 1 graphically replicates part of the information shown in Table 2 and highlights the comparison between the experimental sample during TW (white bars) and the control sample (black bars) during GW. The vertical bars show the mean (SD) of the parameters, presented on the ordinate, across the three age groups, presented on the abscissa.

An increase in stride time and step length and a decrease in cadence were associated with increasing age. The single-stance time, as a percentage of stride time, covers a mean value of  $36.69 \pm 1.51\%$  of the stride time across all age classes.

When the study sample (TW) and the reference control sample (GW) were compared, walking speed differed by 13.19% in the 5–6-year age class, 0.61% in the 7–8-year age class, and 2.27% in the 9–13-year age class. The cadence did not vary while the step length was 9.19, 3.57, and 2.30% shorter in the 5–6-, 7–8-, and 9–13-year age classes, respectively. It is noteworthy that the step length decrease during TW showed a tendency to reduce with age.

Figures 2–4 refer to the 5–6-, 7–8-, and 9–13-year age groups, respectively. In the three rows of panels from the top, each figure provides a graphic summary of sagittal joint rotations, joint power, and sEMG voltage (on the ordinate; see legend for muscle labeling) during a stride, respectively. Results are presented as a function of the percentage standardized stride time (on the abscissa). The relative single-stance and double-stance phases are shown as white and black horizontal bars above the abscissa, respectively. In the upper two rows of panels, the white and the black bands refer to results from TW and from GW in the control sample, respectively. The gray band represents the overlap between the white and

**Table 1 Characteristics of study participants across age groups (demographic and anthropometric variables)**

	5–6 years old		7–8 years old		9–13 years old	
	Experimental group	Control group	Experimental group	Control group	Experimental group	Control group
Number of participants	6	10	6	12	8	12
Sex (male/female)	1/5	5/5	4/2	6/6	3/5	7/5
Age (years)	5.83 (0.41)	5.60 (0.51)	7.83 (0.41)	7.60 (0.53)	11.00 (1.31)	11.00 (1.24)
Height (m)	1.19 (0.07)	1.16 (0.06)	1.35 (0.09)	1.29 (0.09)	1.48 (0.07)	1.48 (0.08)
Weight (kg)	24.07 (5.78)	21.96 (2.62)	31.48 (8.00)	27.86 (6.03)	42.30 (5.44)	42.77 (10.75)
Lower limb length (m)	0.61 (0.04)	–	0.69 (0.10)	–	0.79 (0.05)	–

Values of age, height, weight, and lower limb length are reported as mean (SD).

Given the small numbers at hand, significance was not tested for frequency data.

Within each age group, a *t*-test (unpaired, unequal variances) was performed on age, height, and weight.

No statistically significant differences emerged.

Table 2 Spatiotemporal gait parameters across age groups

	5–6 years old			7–8 years old			9–13 years old		
	TW	GW-control	GW	TW	GW-control	GW	TW	GW-control	GW
Walking speed (m/s)	0.83 (0.05)	0.96 (0.29)	1.00 (0.26)	1.08 (0.04)	1.09 (0.19)	1.25 (0.24)	1.08 (0.07)	1.10 (0.20)	1.21 (0.15)
Cadence (steps/min)	132.23 (10.91)	138.14 (14.22)	126.94 (7.07)	129.67 (2.46)	126.09 (16.47)	129.10 (4.91)	121.76 (6.49)	120.23 (13.76)	121.92 (9.06)
Step length (m)	0.38 (0.05)	0.42 (0.02)	0.47 (0.11)	0.50 <sup>b</sup> (0.02)	0.52 (0.02)	0.60 <sup>b</sup> (0.06)	0.54 (0.03)	0.55 (0.02)	0.58 (0.05)
Stride time (s)	0.91 (0.07)	0.88 (0.09)	0.95 (0.06)	0.92 (0.02)	0.97 (0.13)	0.97 (0.13)	0.99 (0.05)	1.01 (0.11)	0.96 (0.12)
Single stance (%)	36.76 <sup>a</sup> (1.62)	40.31 <sup>a</sup> (2.64)	—	37.43 <sup>b</sup> (1.60)	40.30 <sup>b</sup> (2.02)	—	36.07 <sup>a</sup> (1.24)	39.53 <sup>a</sup> (2.22)	—

Values are reported as mean (SD).

The apex symbols (a,b) highlight the significant contrasts after a *t*-test (unpaired; unequal variances) and Bonferroni's correction for multiplicity.

GW, ground walking, experimental group; GW-control, results taken from a sample walking overground on a floor-mounted platform [courtesy of Professor Victoria L. Chester (*et al.*, 2006)]; TW, treadmill walking, experimental group.

<sup>a</sup>TW vs. GW-control.

<sup>b</sup>TW vs. GW.

the black bands. A continuous gray band indicates that the means of the two samples are separated by less than 2 SD so that their difference is not significant at *P* value less than 0.05 (Tesio and Rota, 2008).

The horizontal segments below the sEMG tracings show the 'on' pattern provided by another control study (Agostini *et al.*, 2010) (see the Participants and methods section).

With respect to the joint rotation and power tracings (upper two rows), it is remarkable that no interruption in the gray bands was recorded. However, a trend can be detected for a more flexed joint posture during TW, compared with GW in controls, for the 5–6-year class, only (Fig. 2, note the consistently higher mean values for hip and knee flexion, and ankle dorsiflexion). In particular, as a grand-mean, the maximum ankle plantar flexion was  $0.08 \pm 4.02^\circ$  in TW versus  $19.77 \pm 5.13^\circ$  in GW. Consistently enough, the absorbed power at the hip peaks at  $0.40 \pm 0.31$  versus  $0.17 \pm 0.27$  W/kg and the generated power at the ankle peaks at  $1.35 \pm 0.32$  versus  $2.11 \pm 1.02$  W/kg in TW and GW, respectively. Fewer marked differences can be observed in the 6–7- and the 8–9-year age groups.

With respect to the experimental sEMG tracings (third row of the panels from the top), the recorded waveforms are quite consistent with the underlying pattern of on-off sequences provided by the control study, although in the latter, the data were not grouped by age.

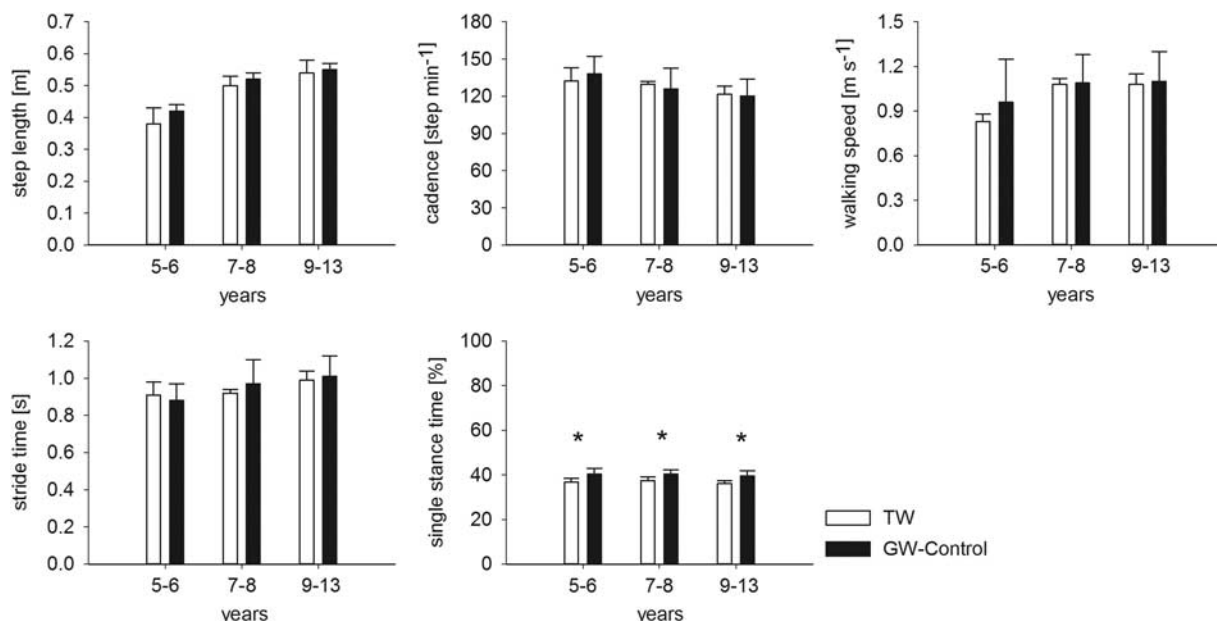
## Discussion

The recent GAFT method was validated for adult gait (Tesio and Rota, 2008), thus justifying its application to subsequent studies in both normal and pathological gait. These covered the topics of the analysis of mechanical energy changes (Rota *et al.*, 2016) and the trajectory (Tesio *et al.*, 1998a, 1998b) of the body center of mass, and of the lower limb joint dynamics (Tesio *et al.*, 2017). However, for the reasons described in the introduction, these favorable findings needed confirmation in children gait. The present study seems to provide such a confirmation.

### Reliability of force-related parameters

Despite the lower weight of children, compared with adults, and thus the potentially higher signal-to-noise ratio, no relevant increases in the variability of force-derived signals were detected. This can be appreciated from the SD of spatiotemporal parameters (foot-ground contacts are detected by vertical forces exceeding 9 N) and of joint power curves. These are very similar between the 5–6-year age group (the least weighting) in the present study and the adult group studied in the GAFT validation article (Tesio and Rota, 2008) (compare Table 1 in both studies and Fig. 2 in the present study with Fig. 4 in the adult study).

Fig. 1



Graphical summary of spatiotemporal gait parameters. In the upper row, from left to right, the three panels refer to step length (m), step cadence (steps/min), and speed (m/s), respectively. In the lower row, the two panels refer, from left to right, to stride time (s) and single-stance time as a percentage of stride time. The white and black bars are the mean (+SD) of the parameters presented on the ordinate for the experimental sample during treadmill walking (TW) and the control sample walking on a floor with embedded force platforms (GW-control) (Chester *et al.*, 2006), respectively. Pairs of bar are provided for each age group, shown on the abscissa. Asterisks mark the significant pairwise comparison (*t*-test, unpaired, unequal variances,  $P < 0.05$ , Bonferroni's correction for multiplicity; see the Participants and methods section).

### Comparison between treadmill walking and ground walking in children

The experimental and the age-matched and speed-matched control groups presented superimposable spatiotemporal parameters during GW. During TW, the experimental sample adopted a shorter step length (by 9.19–2.30%, depending on the age class), for the same speed, with respect to GW. This effect of TW, possibly representing caution raised by a visual-motor mismatch, has already been described in adults (Zanetti and Schieppati, 2007; Tesio and Rota, 2008) and in children (van der Krogt *et al.*, 2014), and found nonetheless to have little impact on lower limb joint rotations and power output, and their sEMG patterns (Tesio and Rota, 2008). In the present study, the profiles of joint power output during TW showed only minor differences with respect to those recorded in GW of controls. The most relevant finding was a slightly more flexed posture of the hip, knee, and ankle joints and a lower power generated by plantar flexors, again in agreement with the literature (Tesio and Rota, 2008; van der Krogt *et al.*, 2015). Given that the plantar flexors are the main providers of 'external' power during walking (Meinders *et al.*, 1998; Tesio *et al.*, 2017), this is consistent with the shorter step length adopted during TW, allowing a lower power to be exerted against the ground (Cavagna *et al.*, 1988). An acceptable agreement was also found for the sEMG

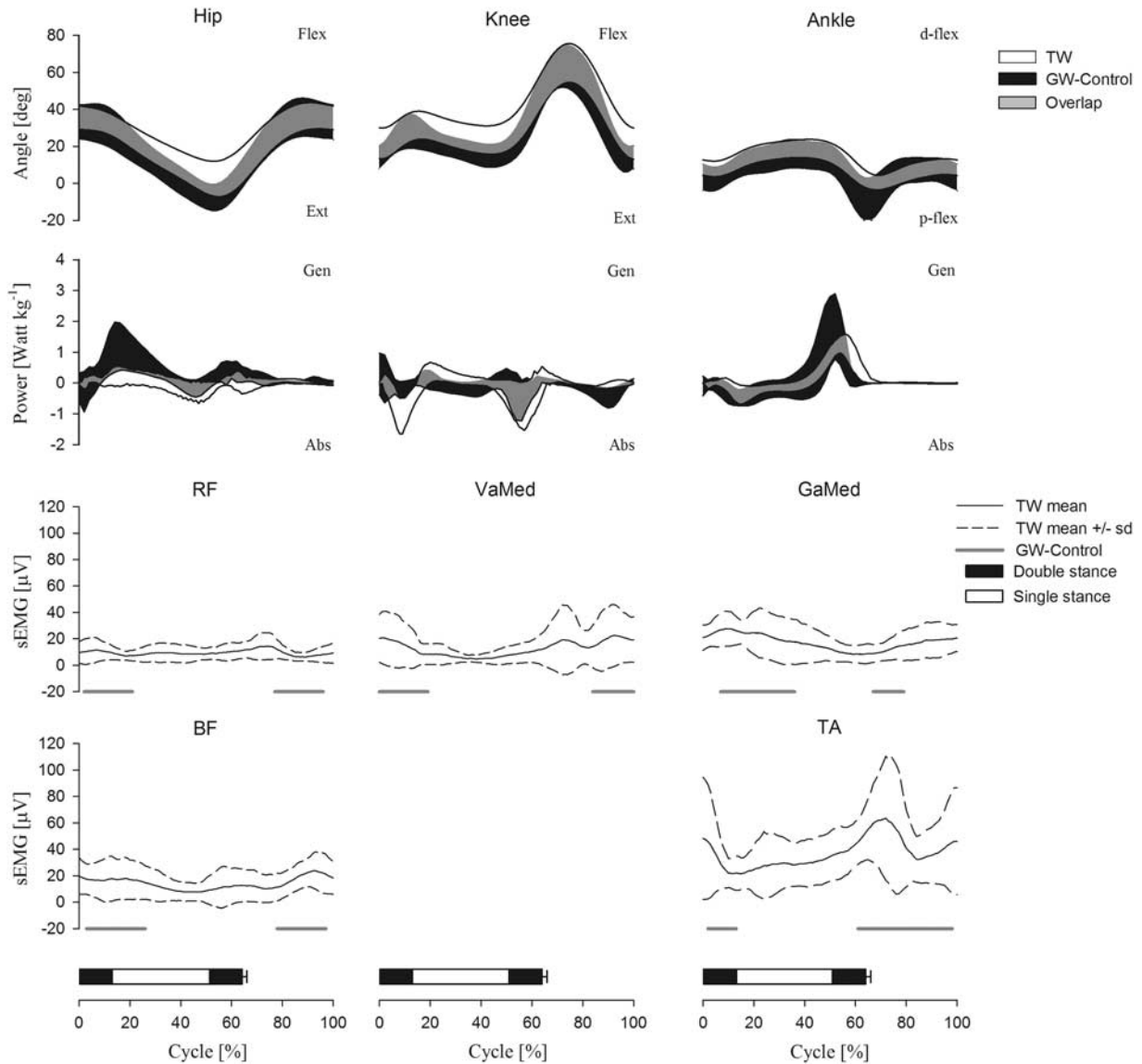
signals between the waveforms recorded during TW and the on-off phases predicted by a control study.

By contrast, the reliability of speed was much smaller in children during GW compared with TW. This is reflected by the SD of the average walking speed being 2–6 times higher, during TW, the more the younger the children; Table 2. This discrepancy was not found in adults and speaks in favor of GAFT when applied to children.

### Comparison with adult data

Both the weight-standardized power values and their variance are in agreement with previous results from a study on adults walking on the same treadmill (Tesio and Rota, 2008). All the mechanical differences found seem to be lower, the older the children, and in the 9–13-year age class, closely mimic those found in adult TW. Step length was 9.19, 3.57, and 2.27% shorter in the 5–6-, 7–8-, and 9–13-year age classes, respectively. This age-related trend may well reflect the maturation of the neuromuscular system (Sutherland *et al.*, 1980; Jeng *et al.*, 1997; Sutherland, 1997); yet, it could partially be an artifact. The gait speed of TW in the experimental group and GW in the control sample could not be perfectly matched, and it was only 0.61 and 2.27% lower in the former, for the 7–8- and the 9–13-year age classes, respectively, but 13.19% lower for the 5–6-year age class.

Fig. 2

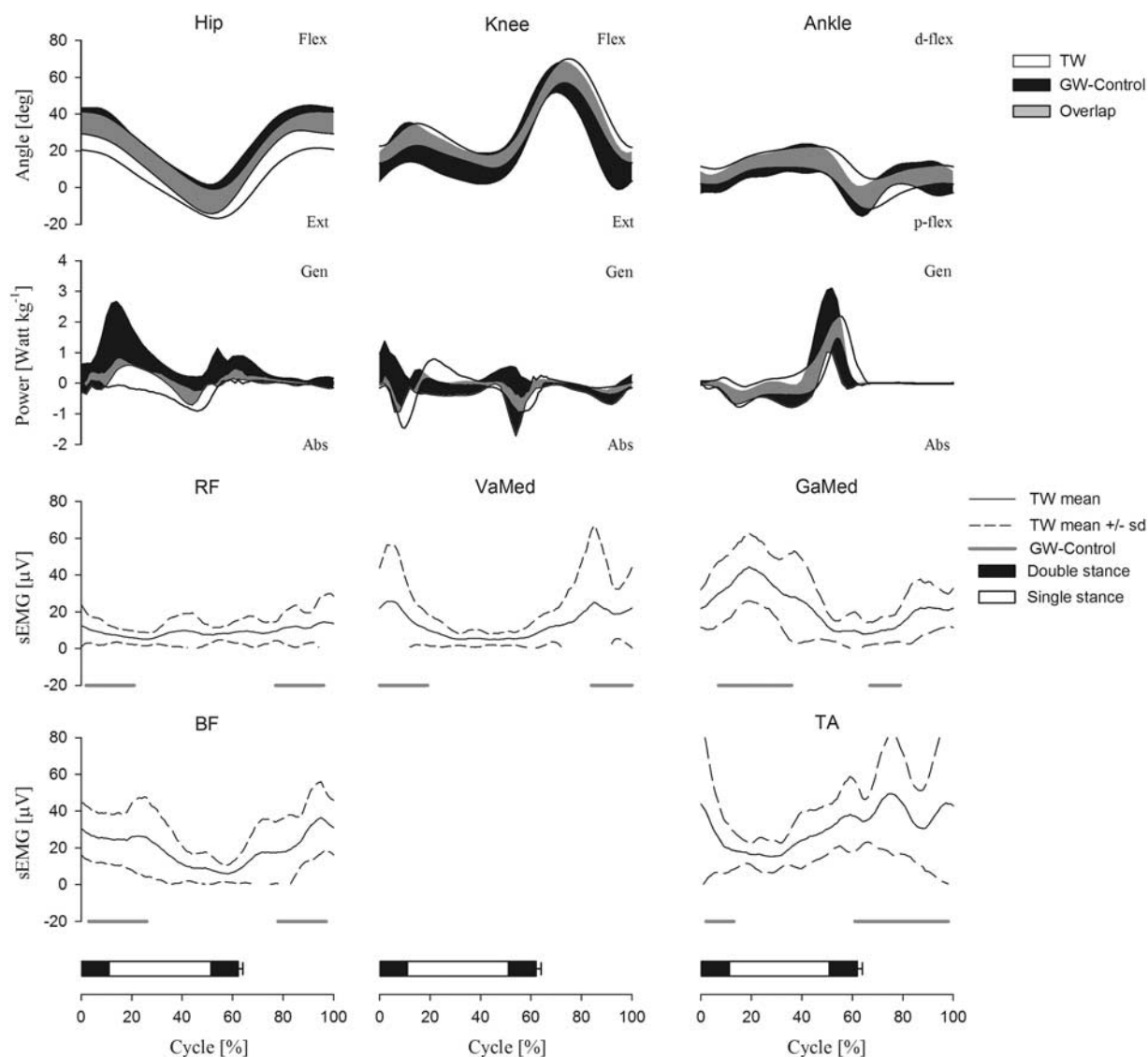


Columns refer to hip, knee, and ankle joints, from left to right, respectively. Results are presented as a function of the standardized stride time (on the abscissa). The relative stance phase (mean  $\pm$  SD) is shown as a horizontal bar above the abscissa. Black and white segments represent the double-stance and the single-stance periods, respectively. Columns refer to hip, knee, and ankle joints, from left to right, respectively. In the three rows of panels from top, the figure shows the sagittal joint rotations, joint power, and surface electromyographic (sEMG) values (on the ordinate), respectively, during a stride. Results are grand-averaged across six subsequent strides in children walking at an average speed of 0.83 m/s and are represented as bands encasing mean  $\pm$  SD. The side of the initial step, within each selected stride, was not predetermined (see the Participants and methods section). For joint rotation and power data, the white bands refer to treadmill walking (TW) in the experimental sample. The black bands represent data from ground walking (GW) in the control sample (Chester *et al.*, 2006). The gray bands represent the overlap between the experimental and the control data. The third and fourth rows of panels from top show the experimental sEMG waveforms recorded from various muscles, identified by specific labels: hip extensors [biceps femoris (BF)] and flexors [rectus femoris (RF)], knee extensors [vastus medialis (VaMed)], and ankle dorsal [tibialis anterior (TA)] and plantar flexors [gastrocnemius medialis (GaMed)]. The continuous and the dashed lines provide mean and mean  $\pm$  SD, respectively. The horizontal segments under each sEMG tracing shows the 'on' periods of muscle activation, given as a percent of the gait cycle, from a previous study (100 healthy children aged 6–11 years walking overground) (Agostini *et al.*, 2010).

The sequence of sEMG activities also closely mimics in all age classes those found in adults (Wootten *et al.*, 1990; Whittle, 2007; Tesio and Rota, 2008). Interestingly enough, also the SD of the sEMG waveforms is comparable to the SD found in adults, at variance with an

article showing that in children aged  $6.5 \pm 2.3$  years (Granata *et al.*, 2005), the variance of the waveforms was twice as large compared with adult sEMG. In the latter study, however, the variance in mechanical gait parameters (e.g. speed and step length) was also higher.

Fig. 3



The panels replicate the information shown in Fig. 2. The experimental data on TW refer to six 7–8-year-old children walking on the force treadmill at an average speed of 1.08 m/s.

Again, this discrepancy speaks in favor of the greater reliability of the results obtainable during TW in children, because of the constant imposed average speed. The findings on the sEMG waveforms are even more interesting if one considers that the smaller size of the children's lower limbs, compared with adults, increases the probability for cross-talk across signals from different muscles.

The near equivalence between TW and GW is mostly sustained by the very small differences (not reaching significance within the present sample) found for power measurements (Figs 2–4, second row of panels from the top). This also speaks in favor of the accuracy and the reliability of the apparatus. Power is computed indirectly

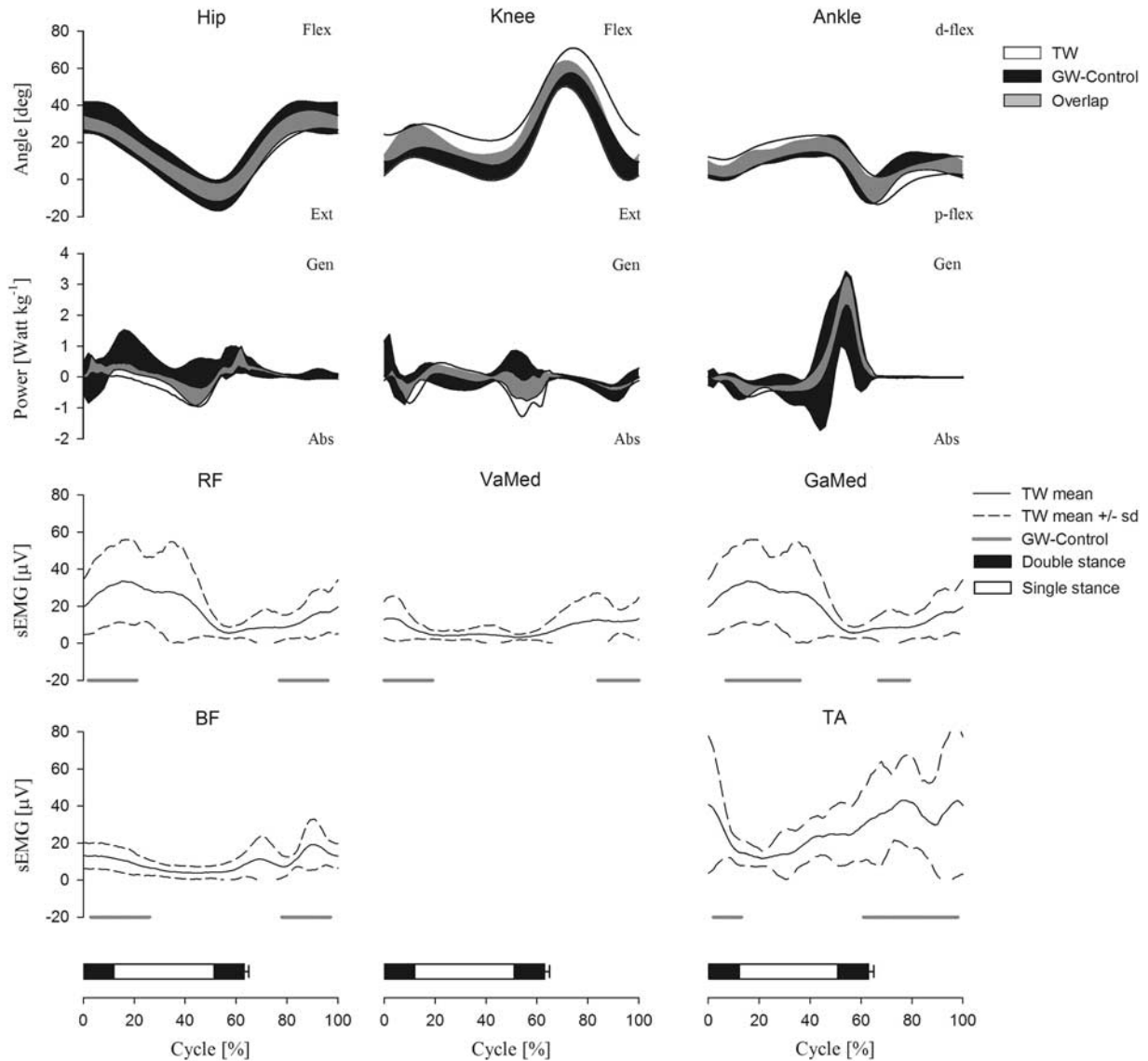
from the 3D motion of skin markers that are spatio-temporally superimposed to the vector of the ground reactions arising under the foot. Therefore, this variable is the most prone to error propagation, potentially caused by the interaction between markers displacements with respect to the underlying bone (soft-tissue artifacts) (Cappozzo *et al.*, 2005; Leardini *et al.*, 2005), forward slipping of the belt at foot impact, and force signal-to-noise ratio.

#### Children compliance

Nowadays, children are increasingly more used to electronic games, so that it is not surprising that they interpreted the experimental setting, including video cameras, computers,



Fig. 4



The panels replicate the information shown in Fig. 2. Data refer to eight 9–13-year-old children walking on the force treadmill at an average speed of 1.08 m/s.

markers, sEMG probes, and a treadmill, as an enjoyable game and an exciting challenge. However, for the same reason, they were easily distractible, particularly at younger ages. The imposition of gait speed and the very short duration of the tests were found to be optimal for easy acquisition of reliable results.

The limitations of this study cannot be underestimated. First, the experimental sample size of 20 is medium, for this kind of studies, but quite small when fractionated across the three age classes. Second, the sample sizes in the present and the control study were asymmetric (6 participants vs. 10 participants in the 5–6-year age group, 6 participants vs. 12 participants in the 7–8-year

age group, and 8 participants vs. 12 participants in the 9–13-year age group, respectively). In addition, TW in a sample was compared with GW in another sample from another study. These differences might have biased the statistical findings toward nonsignificance of the mean differences computed between the two studies. However, as reported in the Participants and methods section, the GAFT method leads to a sharp decrease in within-step variance compared with GW at the same average speed. This may compensate for other sources of error variance, thus increasing the power of statistical testing. Third, the results cannot be extrapolated to children younger than 5 years, thus preventing the analysis of gait maturation. Fourth, only one average speed could be tested for each age

class. Finally, some mechanical differences, however mild they may be considered, remain between TW and GW.

This notwithstanding, the advantages of GAFT, with special reference to the possibility to record several, highly reproducible strides in a matter of seconds, makes it very interesting for the clinical study of children's gait. GAFT thus appears to be a promising alternative to conventional GA on the basis of ground-based force platforms.

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## Conflicts of interest

There are no conflicts of interest.

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