

Technical note

## Evaluation of an ambulatory system for gait analysis in hip osteoarthritis and after total hip replacement

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### Abstract

Spatial and temporal parameters of gait have clinical relevance in the assessment of motor pathologies, particularly in orthopaedics. A new gait analysis system is proposed which consists of (a) an ambulatory device (Physilog<sup>®</sup>) including a set of miniature gyroscopes and a portable datalogger, and (b) an algorithm for gait analysis. The aim of this study was the validation of this system, for accuracy and clinical applicability. Eleven patients with coxarthrosis, eight patients with total hip arthroplasty and nine control subjects were studied using this portable system and also a reference motion analyzer and force plate. The small differences in the stance period ( $19 \pm 31$  ms), stride length and velocity ( $0.4 \pm 9.6$  cm and  $2.5 \pm 8.3$  cm/s, respectively), as well as thigh and shank rotations ( $2.4 \pm 4.3^\circ$  and  $0.3 \pm 3.3^\circ$ , respectively), confirmed good agreement of the proposed system with the reference system. In addition, nearly the same accuracy was obtained for all three groups. Gait analysis based on Physilog<sup>®</sup> was also in agreement with their Harris Hip Scores (HHS): the subjects with lower scores had a greater limp, a slower walking speed and a shorter stride. This ambulatory gait analysis system provides an easy, reproducible and objective method of quantifying changes in gait after joint replacement surgery for coxarthrosis.

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### 1. Introduction

Gait analysis [1] can be used for evaluating improvements after an intervention to improve walking. Comprehensive gait analysis usually includes kinematics, kinetics and electromyography [2] and this complex information can only be obtained in a dedicated laboratory. Kinematics, kinetics and electromyography are fundamental to characterize gait patterns and their underlying mechanisms [3,4]. However, simplified analysis using spatio-temporal parameters, for example, or comparisons between populations can also be valuable clinically and a portable device may be advantageous for these types of applications. Usually, portable devices only provide a few measurements, typi-

cally spatio-temporal using foot switches [5] or joint angles from electrogoniometers [6]. They have a limited accuracy that depends on the measuring device itself and also on how they are attached to the patient. However, they have the advantage of not requiring a gait analysis laboratory, are easy to use even by non-expert operators and provide results quickly, which are easy to interpret.

One potential application of a portable device for gait analysis could be in the field of hip or knee arthroplasty. Although functional scores are used widely to assess change the patients' responses are often subjective and the disparity between the patient's and doctor's evaluations significant [7,8]. Similarly, radiological signs do not always correlate with functional outcomes of arthroplasty [9,10]. Therefore, objective, dynamic and quantified data from gait analysis could be of additional interest to integrate with other clinical and instrumental data. A portable system may expand the clinical use of gait analysis.

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In this study, a new gait analysis system is proposed which consists of (a) an ambulatory device (Physilog<sup>®</sup>) including a set of miniature gyroscopes and a portable datalogger, and (b) an algorithm for gait analysis. The aim of this study is to show the applicability of this ambulatory system as a complementary method of gait analysis after hip arthroplasty.

## 2. Methods

### 2.1. Gait analysis using a force plate and an ELITE system

Gait Analysis was performed using a motion analyzer (ELITE system, BTS SrL, Milan, Italy) equipped with four video cameras recording at 100 Hz [11,12]. One 60 cm × 40 cm force plate (Kistler 9661 A) was embedded in the floor about one-third of the way down a 10 m walkway. Signals from the forceplate were collected at 500 Hz. The acquisition protocol has already been described [13]. The retro-reflective markers were positioned as follows: fifth metatarsal head, lateral malleolus, lateral femoral epicondyle, posterior iliac spines and lower edge of sacrum, the posterior process of the seventh cervical vertebra and the point of maximum thoracic kyphosis. Joint kinematics were confined to flexion/extension angles at the hip, knee, and ankle joints.

The spatio-temporal parameters were computed from the initial and terminal contacts of each foot on the ground. The force platform was used to detect the initial contact of one foot and was defined when the ground reaction force achieved a threshold of 5% of body weight. The next contact of the foot on the ground occurred in a non-instrumented area of the floor. Contact was defined when a similar markers' configuration was achieved (same distance from the floor, same displacement) as in the contact detected by the force platform. This method has been described previously [14]. The contralateral side was analyzed by evaluating the distance of the foot from the ground.

### 2.2. Gait analysis using Physilog<sup>®</sup> system

Physilog<sup>®</sup> (BioAGM, CH) is an ambulatory system based on miniature kinematic sensors attached on body segments and a portable recorder placed on the waist belt. The device is lightweight (300 g), compact, can record up to eight channels, allows the storage of up to 16MB of data on a removable memory card and can operate continuously for up to 16h on a rechargeable battery. It thus offers a practical method of gait analysis during daily activities. In this study, lower limb movement during walking was measured using four miniature gyroscopes (Murata, ENC-03J) attached, respectively, to each shank and each thigh (Fig. 1). Each sensor measured the angular rotation rate parallel to the medio-lateral axis. The signals were digitized (12 bit) at a sampling rate of 200 Hz by the portable data logger, and



Fig. 1. A subject carrying the Physilog<sup>®</sup> system. The datalogger (300 g) can be fixed around the waist. Each sensor (gyroscope) is attached with elastic strip on each shank and thigh and linked with thin cable to the datalogger.

stored for off-line analysis. An original method based on wavelet analysis was proposed to compute the values of spatial and temporal gait parameters from the angular velocity of the lower limbs [15]. First, gait phases were determined from the precise moments of left initial contact (IC<sub>L</sub>), left terminal contact (TC<sub>L</sub>), right initial contact (IC<sub>R</sub>) and right terminal contact (TC<sub>R</sub>). Every temporal parameter of a gait cycle,  $k$ , was computed as a percentage of this gait cycle as shown in Fig. 2. These parameters were the duration of stance, swing, initial double stance (IDS), terminal double stance (TDS), the sum of initial and terminal double stance corresponding to double support (DS) and the absolute difference of initial and terminal double stance (ADDS). Spatial parameters were estimated by integrating the angular rate of rotations of the thigh and shank. The maximum and minimum of each angle during each cycle was detected. The difference between the maximum and minimum angles was considered as the range of rotation and based on these values the following angular parameters were computed and compared to the ELITE system:

- range of rotation for left and right thigh:  $R\alpha_L, R\alpha_R$ ;
- range of rotation for left and right shank:  $R\beta_L, R\beta_R$ ;
- range of rotation around left and right knee:  $R\gamma_L, R\gamma_R$ .

In addition, the stride length (SL) and stride velocity (SV) were divided by the height of each subject for normalization purposes.

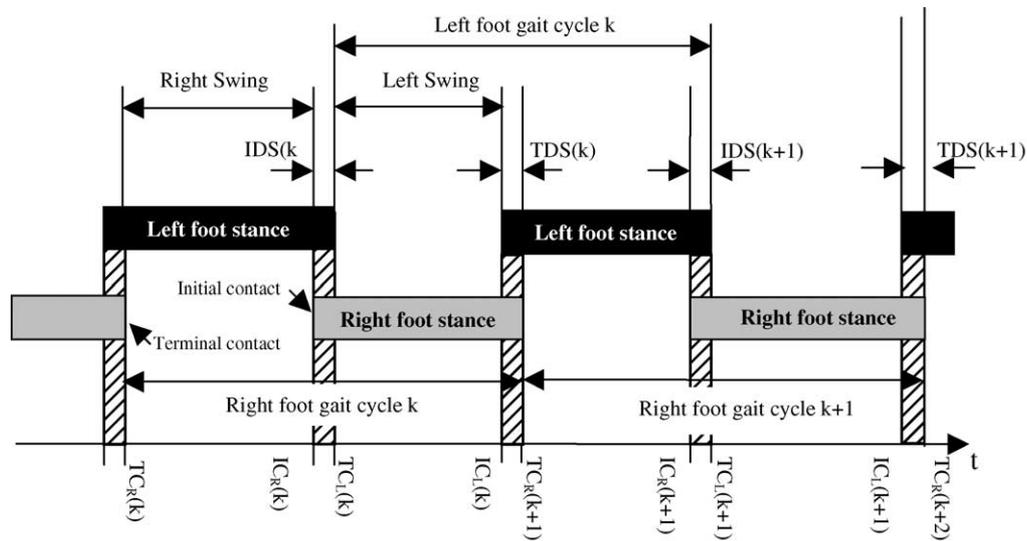


Fig. 2. Gait phases during two consecutive gait cycles started by the terminal contact of the right foot ( $TC_R(k)$ ). Initial and terminal contact of each foot was estimated from distinctive features of shank angular velocity signal recorded by Physilog<sup>®</sup>. Based on these events, all other temporal parameters were calculated.

To synchronize recordings, the ELITE system, including the force plate, and the portable datalogger were triggered by an external signal. The ELITE and portable systems analyzed the same gait cycle for each trial. Statistical analysis was then performed to determine the significance and accuracy of the parameters obtained by gait analysis algorithm based on Physilog<sup>®</sup> in comparison with the ELITE system. For assessing agreement between the two methods, for each gait parameters, first the difference between estimated and actual values was calculated. Then, the mean difference  $d_m$  and its standard deviation  $S.D._d$  were estimated [16].

### 2.3. Experimental setup

Measurements were taken from three groups. Group A included 11 patients with unilateral coxarthrosis (age:  $60 \pm 9$  years, weight:  $74 \pm 8$  kg, height:  $167 \pm 5$  cm), Group B consisted of eight patients with unilateral total hip prosthesis (age:  $69 \pm 4$  years, weight:  $74 \pm 14$  kg, height:  $167 \pm 10$  cm, time from surgery 18–36 months) and Group C comprised nine healthy subjects who were age matched to the two other groups and served as controls (age:  $63 \pm 4$  years, weight:  $63 \pm 9$  kg, height:  $161 \pm 10$  cm). All patients in Group A had an indication for a hip replacement, but were otherwise healthy. The patients in Group B had a well-tolerated hip prosthesis with no radiological signs of loosening and were otherwise healthy at the time of examination.

Each patient walked at a self-selected and performed 6–10 trials (half were with left initial contact and the other half with right initial contact). The exact time of initial and terminal contacts extracted by both of the systems were compared.

In addition, seven patients from Group A, six patients from Group B and eight subjects from Group C completed

the Harris Hip Score (HHS) [17]. The following gait parameters were considered and correlated with this score: percentage of double support (DS, %), absolute difference in double support percentage (ADDS, %), normalized stride length (SL, –), normalized stride velocity (SV, 1/s) and range of rotation ( $^{\circ}$ ) of thigh ( $R\alpha_L$ ,  $R\alpha_R$ ), shank ( $R\beta_L$ ,  $R\beta_R$ ) and knee ( $R\gamma_L$ ,  $R\gamma_R$ ).

## 3. Results

### 3.1. Comparison between reference and ambulatory systems

A total of 89, 70 and 68 gait cycles were obtained from Groups A, B and C, respectively. For each gait cycle, temporal events (initial and terminal contact, gait cycle and stance) and spatial parameters (range of thigh and shank rotation, stride length and velocity) detected by the forceplate and ELITE system were compared with those estimated from data recorded by Physilog<sup>®</sup>. Table 1 illustrates for each group of subjects and overall gait cycles ( $N = 227$ ), the mean difference  $d_m$  and its standard deviation  $S.D._d$  for each parameter. By considering all the gait cycles, a systematic difference of  $-13$  ms was observed between the actual initial contact (from the forceplate) and the corresponding value estimated from the proposed method. This difference reached 7 ms for terminal contact. Over all gait cycles, the initial contact was detected slightly later, while terminal contact occurred a little earlier than with the forceplate. The same trends were observed for the different groups of subjects except in Group B where terminal contact was detected slightly later ( $-3.4$  ms). The error of the estimation was based on  $S.D._d$  which ranged from 13 to 31 ms. A linear

Table 1

Mean difference ( $d_m$ ) and its standard deviation (S.D. $_d$ ) for gait events (initial and terminal contact, gait cycle, stance time) and spatial parameters (stride length and velocity, range of thigh and shank rotation) obtained for each group and by considering all subjects (overall)

	Group			Overall
	A	B	C	
<b>Initial contact</b>				
$d_m$ (ms)	-8.7	-13.6	-16.6	-12.6
S.D. $_d$ (ms)	16.8	10.48	11.90	14.0
<b>Terminal contact</b>				
$d_m$ (ms)	16.6	-3.4	3.7	6.6
S.D. $_d$ (ms)	22.8	34.9	26.5	29.2
<b>Gait cycle</b>				
$d_m$ (ms)	-0.3	3.6	4.8	2.4
S.D. $_d$ (ms)	24.6	26.4	20.7	24.1
<b>Stance</b>				
$d_m$ (ms)	25.3	10.2	20.4	19.2
S.D. $_d$ (ms)	28.3	35.0	29.6	31.4
<b>Stride velocity</b>				
$d_m$ (cm/s)	2.7	2.5	2.4	2.5
S.D. $_d$ (cm/s)	9.2	8.7	6.5	8.3
<b>Stride length</b>				
$d_m$ (cm)	1.3	-0.2	-0.1	0.4
S.D. $_d$ (cm)	8.5	11.4	8.9	9.6
<b>Thigh rotation range</b>				
$d_m$ (°)	2.6	1.7	2.9	2.4
S.D. $_d$ (°)	3.5	5.3	3.7	4.2
<b>Shank rotation range</b>				
$d_m$ (°)	-0.5	-0.2	-0.3	0.3
S.D. $_d$ (°)	3.1	2.9	3.8	3.3

relationship existed between the actual ( $GCT_a$ ,  $ST_a$ ,  $R_a$ ,  $SV_a$ ,  $SL_a$ ) and the data measured using Physilog<sup>®</sup> ( $GCT_m$ ,  $ST_m$ ,  $R_m$ ,  $SV_m$ ,  $SL_m$ ). When including all subjects, the following linear regression was obtained:

Gait cycle:

$$GCT_m = 0.94GCT_a - 0.06, \quad r = 0.97 \quad (1)$$

Stance:

$$ST_m = 1.05ST_a - 0.06, \quad r = 0.90 \quad (2)$$

Range of rotation:

$$R_m = 0.90R_a + 0.16, \quad r = 0.83 \quad (3)$$

Stride velocity:

$$SV_m = 0.80SV_a + 0.18, \quad r = 0.83 \quad (4)$$

Stride length:

$$SL_m = 0.88SL_a + 0.14, \quad r = 0.79 \quad (5)$$

where  $r$  is the coefficient of correlation.

When considering each group separately, the slope and intercept were also close to the value of equation above.

### 3.2. Comparison between clinical scores and ambulatory system

Individual data of clinical scores and gait parameters obtained in the three groups are summarized in Table 2. When gait parameters were considered, ADDS, SL and SV showed significantly lower performances (higher double support difference, smaller stride length and lower stride velocity) in Group A as compared to Groups B and C, whereas no differences were observed in the DS. To compare the rotations results, the data were grouped in four subgroups: affected side in Group A, affected side in Group B, right and left sides in Group C and healthy unaffected sides in Groups A and B. A significant difference between the four combined subgroups was found only at the thigh where the rotation of the affected side in patients with coxarthrosis was significantly worse than the affected side in Group B, in the control subjects, and in the unaffected side in Groups A and B ( $P < 0.01$ ). However, no difference was found at the shank and knee level.

## 4. Discussion

Kinetic, kinematic and electromyographic data may provide sophisticated information about functional impairment and abnormal gait patterns and their use is well established [18]. Most systems are not practical for daily activities and so we have introduced a portable gait analysis system, which is easy to use even by non-expert operators.

One problem for a portable system is to ensure that the computed parameters are correct and corresponds to measurements by more sophisticated systems. Our portable system showed good agreement with the ELITE system for stride length and velocity, and thigh and shank rotations (Table 1). Assuming this difference as a consistent bias of our method (systematic error), the measured values can be corrected by considering these differences. If necessary, linear approximations as in Eqs. (1)–(5) can also be applied to modify measured values by their linear approximations. The errors (S.D. $_d$ ) for initial and terminal contacts, gait cycle as well as stance period, were low compared to the time resolution of the ELITE and Physilog<sup>®</sup> systems, the inherent error of the measurement, as well as the estimation error of ELITE system [14]. When considering an average gait cycle of 1.14 s (the mean overall for the subjects) this error correspond to less than 3% of a gait cycle. With regards to spatial parameters, by considering a mean stride length of 1.2 m, a mean stride velocity of 1.1 m/s, the standard error was less than 8%. The same percentage of error was observed for the rotation ranges. The estimation error for slower limb rotations, and stride length and velocity was principally due to the inaccuracy of the gyroscopes that induced some error on the estimation of thigh and shank rotations. Other factors such as the difficulty in measuring the exact shank and thigh length, the misalignment of the gyroscope axis in the

Table 2

Individual values of clinical scores and temporal and spatial gait parameters in 21 subjects divided in patients with coxarthrosis (Group A), patients with operated of total hip arthroplasty (Group B) and control subjects (Group C)

	Affected side	HHS total	DS (%)	ADDS (%)	SV (1/s)	SL (-)	$R\alpha_L/R\alpha_R$ (°)	$R\beta_L/R\beta_R$ (°)	$R\gamma_L/R\gamma_R$ (°)
Group A									
1	Left	50	16	4	0.65	0.64	<u>36/32</u>	<u>66/57</u>	<u>54/58</u>
2	Left	47	21	3	0.59	0.6	<u>27/38</u>	<u>59/56</u>	<u>51/58</u>
3	Left	59	23	5	0.56	0.63	<u>32/37</u>	<u>63/60</u>	<u>50/58</u>
4	Right	67	23	3	0.46	0.53	<u>25/23</u>	<u>59/58</u>	<u>62/51</u>
5	Right	54	15	2	0.59	0.69	<u>43/34</u>	<u>77/71</u>	<u>50/55</u>
6	Right	90	19	5	0.65	0.7	<u>40/38</u>	<u>73/68</u>	<u>59/57</u>
7	Left	51	18	4	0.56	0.62	<u>34/37</u>	<u>71/63</u>	<u>60/54</u>
Mean		60 <sup>a</sup>	19 NS	4 <sup>b</sup>	0.58 <sup>c</sup>	0.63 <sup>c</sup>	<u>32<sup>d</sup>/36</u>	<u>65 NS/64</u>	<u>54 NS/57</u>
S.D.		15	3	1	0.06	0.06	<u>5/6</u>	<u>5/8</u>	<u>4/4</u>
Group B									
8	Left	62	17	2	0.57	0.6	<u>34/35</u>	<u>64/62</u>	<u>54/54</u>
9	Right	81	17	3	0.55	0.64	<u>31/33</u>	<u>63/57</u>	<u>49/43</u>
10	Right	100	27	3	0.61	0.74	<u>52/41</u>	<u>74/68</u>	<u>63/50</u>
11	Right	96	17	2	0.65	0.72	<u>37/40</u>	<u>77/72</u>	<u>64/57</u>
12	Right	100	14	5	0.74	0.78	<u>50/38</u>	<u>80/72</u>	<u>67/60</u>
13	Left	83	14	3	0.64	0.72	<u>42/40</u>	<u>73/69</u>	<u>64/58</u>
Mean		87	18	3	0.63	0.70	<u>38/41</u>	<u>68/71</u>	<u>55/59</u>
S.D.		15	5	1	0.07	0.07	<u>4/8</u>	<u>6/7</u>	<u>7/7</u>
Group C									
14		100	16	2	0.7	0.68	42/41	73/69	60/58
15		100	18	1	0.61	0.73	45/45	80/74	64/58
16		96	17	2	0.66	0.65	42/42	73/68	61/58
17		96	12	4	0.79	0.72	41/44	74/72	60/62
18		100	21	1	0.79	0.72	37/35	71/67	57/50
19		78	21	2	0.61	0.64	42/37	68/62	61/59
20		97	21	2	0.57	0.7	44/40	73/66	59/54
21		100	11	1	0.8	0.8	42/42	81/77	63/65
Mean		96	17	2	0.69	0.71	42/41	74/69	61/58
S.D.		8	4	1	0.09	0.05	2/3	4/5	2/5

Subscript L and R in angular ranges correspond to left and right side, respectively, where the underlined values show the affected side. NS: difference not significant.

<sup>a</sup> Group A significantly different from Groups B and C, and Group B significantly different from Group C.

<sup>b</sup> Group A significantly different from Group C.

<sup>c</sup> Group A significantly different from Groups B and C.

<sup>d</sup> Group A significantly different from Groups B, C and healthy unaffected sides in Groups A and B.

medio-lateral axis and the error due to gait phase detection, should also be considered. The low values of the intercept (close to 0) and the slope close to 1 in Eqs. (1)–(5), confirm the appropriateness of our estimation.

A second objective was to verify the feasibility of measurements in patients with gait pathology, where extremely low movements or, brisk contractions of muscles can affect the quality of the signals. For this purpose, we changed slightly our previous sensor configuration where only one side angular rotation was estimated [15] by assuming symmetric walking. In this study, left and right lower limb rotations were estimated separately by four gyroscopes attached on each thigh and shank, allowing estimates with the same accuracy of spatio-temporal parameters in control subjects and patients who had a severe limp. One major feature of the proposed method is that we obtained nearly the same accuracy for all three groups (Table 1).

The differences between the three groups were also well documented by the estimated parameters using Physilog<sup>®</sup> data and were in accordance with the clinical scores. Group A recorded the worse performance: patients with coxarthrosis had a significantly worse limp (longer ADDS), walked slower and with a shorter stride, which are typical gait analysis features in hip dysplasia and osteoarthritis [4,19,20]. Group B showed gait parameters very similar to those recorded in the control group, as we expected, since they were up to 18 months from surgery and had good to excellent clinical and radiographic results.

Walking speed, a gait parameter that is able to discriminate the degree of recovery of patients with total hip arthroplasty versus patients with hemiarthroplasty [21], was also different in our three groups. It reached statistical significance between patients with coxarthrosis and controls, while a 9% difference was still detectable between

operated patients and controls. Data consistent with the clinical situation were also observed when rotations were considered. Rotation around the hip (thigh rotation) was significantly reduced in patients with hip arthritis as already reported in other studies [4,19] and its noteworthy that it was not different from what was observed in control subjects, for the unaffected hips of patients with unilateral coxarthrosis (Group A) and for the operated hips in Group B.

We compared patients with hip osteoarthritis, patients operated with total hip arthroplasty and age-matched healthy subjects, with the aim of evaluating the clinical usefulness of a portable gait analysis device. Our results may be affected by the small sample size and by the design of the study, nevertheless the congruency of the data and the consistency between clinical and instrumental parameters suggest that gait analysis based on Physilog<sup>®</sup> can provide an easy, reproducible and objective method to quantify the expected gait improvement after the hip replacement.

Physilog<sup>®</sup> is a portable device for gait analysis that does not hinder the subject during his natural walking. Contrary to standard gait analysis devices, gait analysis based on Physilog<sup>®</sup> is not limited to a laboratory setting and it can be used in outpatient settings, where gait parameters can be recorded for up to 7 h per day [22]. The objective assessment of gait in outpatient may greatly improve our future ability to compare effectiveness of different surgical procedures, prosthetic designs or rehabilitative protocols.

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