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Reliability of IMU-Derived Gait Parameters in Foot Drop Patients

Armando COCCIA[a,b,1], Federica AMITRANO[a,b], Gaetano PAGANO[a], Arcangelo BIANCARDI[a], Giuseppe TOMBOLINI[c] and Giovanni D'ADDIO[a]
[a] *Scientific Clinical Institutes ICS Maugeri SPA SB, Pavia, Italy*
[b] *University of Naples 'Federico II', Naples, Italy*
[c] *Officine Ortopediche Tombolini, Taranto, Italy*

Abstract. Foot drop is a deficit in foot dorsiflexion causing difficulties in walking. Passive ankle-foot orthoses are external devices used to support the drop foot improving gait functions. Foot drop deficits and therapeutic effects of AFO can be highlighted using gait analysis. This study reports values of the major spatiotemporal gait parameters assessed using wearable inertial sensors on a group of 25 subjects suffering from unilateral foot drop. Collected data were used to assess the test-retest reliability by means of Intraclass Correlation Coefficient and Minimum Detectable Change. Excellent test-retest reliability was found for all the parameters in all walking conditions. The analysis of Minimum Detectable Change identified the gait phases duration and the cadence as the most appropriate parameters to detect changes or improvements in subject gait after rehabilitation or specific treatment.

Keywords. Foot Drop, Ankle-Foot Orthosis, Gait Analysis, Inertial Measurement Unit, Intraclass Correlation Coefficient.

1. Introduction

Foot drop is a common deficit characterised by the difficulty in performing foot dorsiflexion, causing the front part of the foot to drag along the ground while walking. This severely affects gait functions: at heel strike, the forefoot generally impacts to the ground in an uncontrolled and rapid manner; during foot swing, the inability to lift the front part of the foot causes the toes to drag on the ground with consequent high risk of stumbling and falling [1]. The Codivilla spring is an ankle foot orthosis (AFO) designed to enhance control in walking and postural tasks, improving the quality of life of people suffering from this pathology [2]. This orthosis is made of thermoplastic material with an L-shape, with a rigid sole supporting the foot and a posterior leaf attached to the calf. The structure acts as a spring, returning elastically the flexion forces imparted during the terminal stance phase loading of the ankle. The effects of using these orthoses are generally qualitatively detectable from the observation of subjects walking. However, using gait analysis methodologies, the biomechanics of patients' gait can be studied to understand whether and how the use of the orthosis improves their walking. Based on these studies, it is also possible to customise the orthosis for specific purposes [3].

[1] Corresponding Author: Armando Coccia, E-mail: armando.coccia@icsmaugeri.it.

In foot drop patients abnormal plantarflexion is detectable during gait phases [4], while the use of an AFO determines improvements in walking speed, step frequency, stride and step length and functional ambulation ability [5–7]. In [8] significant differences were outlined between the affected and healthy limb in foot clearance at mid-swing and duration of the stance and swing phases. The step duration also significantly differed among limbs and improves when walking with AFO. While the effects of the orthotic devices on walking have been widely discussed in previous literature, it seems to lack the analysis of reliability of gait analysis metrics for this kind of deficit. Therefore, the aim of this study is to explore the intra-session test-retest reliability of the major spatio-temporal gait parameters measured on a cohort of foot drop patients using a system based on wearable Inertial Measurement Units (IMUs). Test-retest reliability represents a basic methodological study for clinical settings, as it validates the reliability of the measurement setting [9]. Moreover, the analysis of derived metrics, such as the Minimum Detectable Change (MDC), can also suggest which parameter or pattern is more suitable to characterize a specific pathological scenario.

2. Methods

2.1. Experimental Procedure

Twenty-five patients (17 males, 8 females), with unilateral foot drop syndrome (14 right, 11 left foot), were involved in this research (age 56.6 ± 13.5, BMI 23.3 ± 4.2). The Mobility Lab system by APDM (APDM Inc, Portland, OR, USA, http://apdm.com) was used to perform gait analysis on the study population. The experimental sessions were performed in the Movement Analysis Laboratory of the ICS Maugeri in Bari (Italy), and consisted of three repeated walking trials. Three body worn IMUs were used: one on the low back (just below L5 level) and two on the dorsal surface of the feet. The IMUs, measuring 43.7 x 39.7 x 13.7 mm (LxWxH), wireless transmit data sampled at 128Hz to an access point connected to the central workstation. In each trial the subject was instructed to stand quietly for 30s and then walk at comfortable speed over a 7m walkway, turn around a pivot and walk back to the starting point [10]. Subjects performed two separate sessions, in two different conditions: wearing or not the Codivilla spring on the affected limb. Both sessions were performed with patients wearing shoes. The order of the sessions was randomly selected, to avoid any ordering effects.

The following spatio-temporal parameters were considered in the analysis: foot clearance at mid-swing (cm), gait cycle time (GCT) (s), stance phase (expressed as percentage of GCT), swing phase (%GCT), cadence (steps/min), step duration (s), stride length (m), gait speed (m/s). These metrics were computed considering the gait cycles of each leg, thus producing two datasets for the affected and healthy (contralateral) limbs.

2.2. Statistical Analysis

Paired t-tests were conducted on the subject-averaged values to analyse whether statistically significant changes occur between limbs (affected vs contralateral) and/or walking conditions (walking with AFO or without).

The test-retest reliability over the three repeated trials was assessed using the Intraclass Correlation Coefficient (ICC) [11]. ICC estimates and their 95% confidence intervals (CIs) were calculated, on the four datasets per each spatio-temporal parameter, based on single-measurement, absolute-agreement, 2-way mixed-effects model [12]. The ICC values were interpreted as poor when less than 0.5, moderate between 0.50 and 0.75, good between 0.75 and 0.90 and excellent when above 0.90 [13]. Absolute reliability was obtained using the Minimum Detectable Change (MDC), i.e. the smallest difference needed between separate measures on a subject to be considered a real change. It is calculated from the Standard Error of Measurement (SEM) and ICC as follow [14]: $SEM = SD_{all\ testing\ scores} \cdot \sqrt{(1 - ICC)}$ and $MDC = SEM \cdot 1.96 \cdot \sqrt{2}$. Statistical analyses were performed using R version 4.0.3 (R Foundation, Vienna, Austria).

3. Results

Table 1 reports descriptive statistics of the datasets in terms of mean and standard deviation, and results of paired t-tests. Statistically significant differences between limbs are indicated with an asterisk, while variations between walking conditions with a dagger symbol ($p - value < 0.05$). The test-retest reliability analysis produced the ICC values reported in Table 1. Excellent reliability ($ICC > 0.90$) was found for all the analysed parameters, except for the foot clearance in the healthy limb in walking without the AFO ($ICC = 0.865$). Table 2 also reports MDC values in the unit of the parameter and in percentage of the mean value to facilitate interpretation and comparisons. Low MDC values were found for stance and swing phases and cadence ($MDC\% < 10\%$). Gait cycle time, step duration, stride length and gait speed presented higher values of MDC, but lower than 15% of the mean value. Conversely, very high variability was underlined in foot clearance values over the trials.

4. Discussion and Conclusions

The principal aim of this study was to assess the test-retest reliability of gait analysis metrics on repeated measures performed with a system using three wearable inertial sensors. In the presented results, very high reliability was found for all the analysed parameters. The lowest ICC was found in the measures of healthy foot clearance at midswing when not wearing the AFO. These results showed that the gait analysis system based on three wearable inertial sensors, placed on the low back and on both feet, provides very reliable measures. This is in line with other scientific literature examining the performances of inertial sensors for gait analysis. In [15] high ICC values were found for gait metrics calculated using the APDM Mobility Lab with sensors placed on the ankle. Washabaugh *et al.* [14] found even higher ICC values when the system is used with the wearable sensors on the feet. The high repeatability of gait measures, obtained with inertial sensors, was confirmed also on other groups of patients [16,17] and with different systems and sensor configurations [18–20]. This study also explored the MDC for spatio-temporal gait parameters. The MDC was very low for stance, swing and cadence. Moderate values were found for step duration, stride length, gait cycle time and gait speed, while foot clearance MDC presented very high values. The values are consistent with those proposed by Washabaugh *et al.* [14], found on a group of 39 healthy subjects with analogous instrumentation, however authors did not explore foot clearance at midswing. Results about gait speed are similar to or better than those assessed with other methods [21].

Table 1. Descriptive statistics as mean ± standard deviation. Significant p-value from paired t-test between limbs are indicated with asterisk, while variations in walking conditions with.

	Without AFO		With AFO	
	Affected Foot	**Contralateral Foot**	**Affected Foot**	**Contralateral Foot**
Foot Clearance (cm)	2.29 ± 2.21	1.69 ± 0.77	2.40 ± 1.79	1.69 ± 0.78
Gait Cycle Time (s)	1.48 ± 0.39	1.49 ± 0.39	1.45 ± 0.37	1.45 ± 0.37
Stance (%GCT)	64.8 ± 4.3	67.2 ± 6.2*	64.5 ± 6.2	67.1 ± 5.6*
Swing (%GCT)	35.2 ± 4.3	32.8 ± 6.2*	35.6 ± 4.2	32.9 ± 5.6*
Cadence (steps/min)	85.7 ± 18.2	85.6 ± 18.2	87.0 ± 17.1	87.0 ± 17.2
Step Duration (s)	0.77 ± 0.21	0.72 ± 0.19*	0.73 ± 0.18†	0.72 ± 0.19
Stride Length (m)	0.84 ± 0.25	0.85 ± 0.23	0.85 ± 0.22	0.86 ± 0.22
Gait Speed (m/s)	0.63 ± 0.27	0.64 ± 0.27	0.65 ± 0.24	0.65 ± 0.25

Note: step duration, stride length and gait speed means have two significant digits because of gait analysis software limitation

Table 2. Results of test-retest reliability analysis. ICC values are reported with the 95% CI in parentheses. MDC values are expressed in the same unit as the gait parameter and in percentage of the mean value.

	ICC (95%CI)			
	Without AFO		With AFO	
	Affected Foot	**Contralateral Foot**	**Affected Foot**	**Contralateral Foot**
Foot Clearance	0.972(0.945; 0.987)	0.865(0.760; 0.933)	0.979(0.960; 0.990)	0.932(0.870; 0.967)
GCT	0.982(0.962; 0.992)	0.979(0.957; 0.990)	0.979(0.957; 0.990)	0.975(0.950; 0.989)
Stance	0.965(0.933; 0.983)	0.990(0.980; 0.995)	0.966(0.935; 0.984)	0.983(0.967; 0.992)
Swing	0.965(0.933; 0.983)	0.990(0.980; 0.995)	0.966(0.935; 0.984)	0.983(0.967; 0.992)
Cadence	0.981(0.959; 0.991)	0.980(0.958; 0.991)	0.982(0.963; 0.992)	0.982(0.963; 0.991)
Step Duration	0.979(0.958; 0.990)	0.969(0.941; 0.985)	0.976(0.952; 0.988)	0.965(0.928; 0.984)
Stride Length	0.984(0.969; 0.993)	0.985(0.959; 0.994)	0.974(0.949; 0.988)	0.977(0.951; 0.989)
Gait Speed	0.985(0.962; 0.993)	0.984(0.952; 0.994)	0.979(0.956; 0.991)	0.982(0.960; 0.992)
	MDC (MDC%)			
Foot Clearance	1.02(43.7%)	0.786(43.7%)	0.718(29.9%)	0.564(31.1%)
GCT	0.145(9.82%)	0.157(10.5%)	0.147(10.1%)	0.169(11.1%)
Stance	2.23(3.45%)	1.72(2.57%)	2.16(3.35%)	2.00(2.98%)
Swing	2.23(6.33%)	1.72(5.26%)	2.16(6.07%)	2.00(6.10%)
Cadence	6.99(8.15%)	7.15(8.35%)	6.40(7.36%)	6.48(7.44%)
Step Duration	0.0859(11.2%)	0.0909(12.6%)	0.0801(10.9%)	0.0985(13.7%)
Stride Length	0.0850(10.1%)	0.0799(9.38%)	0.0955(11.2%)	0.0934(10.9%)
Gait Speed	0.0924(14.6%)	0.0932(14.6%)	0.0968(15.0%)	0.0931(14.4%)

MDC is the smallest difference needed between separate measures to be considered a real change, so it represents a sort of threshold to assess the effects of rehabilitation. Changes in gait parameters lower than the MDC could be interpreted as measurement errors. This suggests that all the analysed parameters are suitable metrics to evaluate the pathological condition of the subject and to quantify the changes and improvements over time. Conversely, clinicians and researchers should cautiously interpret the variations in foot clearance, considering the variability of the parameter measured by the system, to verify whether it can be considered a relevant improvement for the subject. This confirms the poor discriminative value of the foot clearance metric, as discussed in [22] with a machine learning approach. Some limitations of the work should be mentioned: the study population is limited to 25 patients, a bigger cohort can provide more reliable results; the aetiology of foot drop is varied, this does not allow general assumptions about the cause of the deficit; moreover, patients had been using the orthosis for different periods of time, with different levels of confidence, this can have produced biases in the results. In future works the cohort of analysed subjects will be extended leading to more reliable analyses, which may be also detailed for each single pathology causing the walking deficit.

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