https://doi.org/10.1186/s12984-024-01469-9

Journal of NeuroEngineering and Rehabilitation

RESEARCH **Open Access**

Inertial measurement units to evaluate the efficacy of Equino Varus Foot surgery in post stroke hemiparetic patients: a feasibility study

Nicolas de l'Escalopier[1,2,3†], Cyril Voisard[2†], Sylvain Jung[4], Mona Michaud[2], Albane Moreau[2], Nicolas Vayatis[4], Philippe Denormandie[1,5], Alix Verrando[6], Claire Verdaguer[6], Alain Moussu[6], Aliénor Jequier[6], Christophe Duret[3], Laurence Mailhan[6], Laure Gatin[3,5], Laurent Oudre[4] and Damien Ricard[2,7,8*]

Abstract

Introduction This study evaluates the gait analysis obtained by Inetial Measurement Units (IMU) before and after surgical management of Spastic Equino Varus Foot (SEVF) in hemiplegic post-stroke patients and to compare it with the functional results obtained in a monocentric prospective cohort.

Methods Patients with post-stroke SEVF, who underwent surgery in a single hospital between November 2019 and December 2021 were included. The follow-up duration was 6 months and included a functional analysis using Goal Attainment Scaling (GAS) and a Gait analysis using an innovative Multidimensional Gait Evaluation using IMU: the semiogram.

Results 20 patients had a gait analysis preoperatively and at 6 months postoperatively. 90% (18/20) patients had a functional improvement (GAS T score ≥ 50) and 50% (10/20) had an improvement in walking technique as evidenced by the cessation of the use of a walking aid (WA). In patients with functional improvement and modification of WA the change in the semiogram area was + 9.5%, sd = 27.5%, and it was + 15.4%, sd = 28%. In the group with functional improvement without change of WA. For the 3 experiences (two patients) with unfavorable results, the area under the curve changed by + 2.3%, -10.2% and − 9.5%. The measurement of the semiogram area weighted by average speed demonstrated very good reproducibility (ICC(1, 3) = 0.80).

Discussion IMUs appear to be a promising solution for the assessment of post-stroke hemiplegic patients who have undergone SEVF surgery. They can provide a quantified, objective, reliable in individual longitudinal follow up automated gait analysis solution for routine clinical use. Combined with a functional scale such as the GAS, they can provide a global analysis of the effect of surgery.

Keywords Inertial measurement units, Spastic equinovarus foot, Neuro-orthopaedic surgery, Stroke, Gait analysis

†Nicolas de l'Escalopier and Cyril Voisard contributed equally to this work.

*Correspondence:
Damien Ricard
damien.ricard@m4x.org

Full list of author information is available at the end of the article

Introduction

A frequent chronic complication of post-stroke hemiplegia is the occurrence of a Spastic Equino Varus Foot (SEVF) deformity. This deformity is the cause of significant discomfort in walking and increases the risk of falling. The medical management is based on the use of botulinum toxin and rehabilitation [1]. If medical measures fail, "neuro-orthopaedic" surgery is required to correct dynamic and static deformities [2]. About 18% of stroke survivors will have a SEVF [3], and 59% of these will require surgical management [1].The preoperative evaluation is delicate and relies on consultation between the different actors of the management [4, 5]. Neuro orthopaedic surgery for SEVF encompasses a combination of tendon and nerve procedures performed by a single team [6, 7]. In most cases, the result is satisfactory, allowing the patient to have a plantigrade support for a more stable and fluid gait, sometimes without the need for technical aids. However, precise assessment of the effect of surgery on walking remains difficult and complex to reproduce [8].

The performance of a neuro-orthopaedic surgical procedure in these patients not only has an analytical local impact, but also has a more global repercussion. While the outcome of the procedure can be easily observed during the open chain analytical examination, its repercussion on the patient's global approach remains extremely difficult to evaluate and quantify. Gait assessment of hemiplegic post-stroke patients with SEVF is a real challenge in clinical practice. There is currently no simple, reproducible, objective, and quantifiable way to assess gait in its entirety in clinical practice [8]. For this reason the evaluation of the result is therefore mainly based today on a subjective functional evaluation, with the Goal Attainment Scale (GAS) appearing as the most reliable tool [9–11]. It allows to know if the functional contract established with the patient during the preoperative phase has been fulfilled. Although it provides effective individual-level analysis, it is not very precise when it comes to comparing different treatments [12].

Thus, it seems essential to complete this functional evaluation with a global, quantified and objective evaluation of the repercussion of this procedure on the patients' gait [13].

For several years, the use of inertial measurement units (IMUs) has made it possible to obtain a gait analysis that can be easily deployed in clinical routine [14]. The parameters used have proved highly effective in the longitudinal follow-up of patients suffering from neurological diseases such as Multiple Sclerosis or Parkinsons disease [15–18]. In post stroke patients, several parameters have shown good reliability [19–21]. However, IMUs have never been used in post-operative evaluation in this population. The semiogram is a radar diagram providing an immediate and intuitive view of all the gait data obtained by calculating 17 mathematical parameters validated in the literature and divided into 7 clinical criteria [22, 23]. It offers an instantaneous analysis of gait, which clinicians can conveniently interpret. By combining relevant parameters found in the literature [24, 25], it enables a comprehensive approach based on clinical criteria that can be easily used by the clinician. It therefore seems to us to be a relevant tool for easy use in clinical practice in this indication as a complement of GAS. Indeed it allows for a more detailed and quantified analysis, making it possible, for example, to compare two different interventions, or to assess changes in outcome longitudinally, which is not possible with GAS.

In order to assess the reliability and consistency of semiogram in the peri-operative evaluation of post-stroke SEVF, we compare in this article the results obtained with the semiogram and the functional evaluation usually performed [8]. Validation of IMU analysis by this method will inevitably have the same limitations as GAS, but it remains the best option for comparing clinical data with instrumental data. The originality of our study lies in this mixed approach, as there is currently no way of asserting that an improvement observed instrumentally is necessarily associated with an improvement felt by the patient.

Our main objective is to evaluate the gait analysis obtained by IMU before and after surgical management of SEVF in hemiplegic post-stroke patients and to compare it with the functional results obtained in a monocentric prospective cohort.

Methods

Patients

This was a single-center study (Percy Military Hospital orthopedic and neurophysiology departments, Clamart, France), prospective, longitudinal, non-randomized. Hemiplegic patients with post-stroke equinovarus foot, who underwent surgery at the Percy Hospital between November 2019 and December 2021 were included. The follow-up duration was 6 months. The studies involving humans were approved by Protection des Personnes Nord Ouest III (ID RCB: 2017-A01538-45). The studies were conducted in accordance with the local legislation and institutional requirements. The participants provided their written informed consent to participate in this study. Patients were recruited from the multidisciplinary neuro-orthopedics consultation, including all specialists managing locomotor system neurologic sequelae: physical medicine and rehabilitation, orthopedic surgery, neurology, and physiotherapy. Indications for surgery were thus decided by a specialized team after optimal medical treatment. Patients have been operated at the Percy Hospital by a single surgeon who was present at all consultations.

The inclusion criteria were:

- Age > 18 years;
- Signed informed consent;
- National health insurance cover;
- Spastic equinovarus foot, with treatment by neuro orthopedic procedure indicated by the neuro-orthopedic consultation team;
- Mobile, able to walk 4 times 20 m with U-turn with a pause of 3 min between exercises, with or without walking aid.

The main endpoint was the evaluation of the feasibility and interpretability of the semiogram for evaluation of the efficacity of Equino Varus Foot surgery in post stroke hemiparetic patients, and his comparison with functional analysis obtained by Goal Attainment Scaling (GAS).

Surgical procedure

Surgical management was decided during a multi-disciplinary neuro-orthopaedic consultation. It was comprehensive, incorporating both tendon and nerve procedures, and aligned with the current state of the art [4, 6, 7]. In view of the multitude of possible procedures, we have classified the type of procedures performed into the following four categories: selective neurotomy (SN), tendon lengthening (TL), tendon transfer (TT) (possibly associated with TL).

Gait recording

Gait recording was performed before the surgical procedure and 6 months after. Three IMUs (XSens® MTw Measurement Units; sampling rate, 100 Hz) were used to measure linear acceleration and angular velocity, placed on the dorsal part of the feet, at and in the lower back (L4-L5 vertebrae). The sensors were attached by hook-and-loop fasteners made by the manufacturer. With the sensors attached, the patient performed the following sequence: standing position for 6 s, walking 10 m at comfortable speed, U-turn, walking 10 m at comfortable speed, standing position for 5 s. Patients performed twice the sequence, without walking aid if possible: first with footwear and then barefoot. A computer collected synchronized sensors data.

Clinical data

Functional assessment of the outcome of transfer was made on GAS [9, 10], to provide an objective evaluation of functional success according to the preoperative contract between team and patient. The evaluation of GAS was done at 6 months follow-up. Using a validated form for setting out the objectives to be achieved as part of the GAS in a standardized way, the patient expressed his or her expectations and their relative importance with respect to the disability, and then the patient and the medical team assessed the result postoperatively. If the result was as expected, it scored 0; if better than expected, +1 or +2 depending on how much better; and if there was no functional improvement, then −1 or, if there was any aggravation, -2. Three or four objectives can be assessed, for a total score out of 50. The T score used was:

$$T = 50 + {10 \sum WiXi} \Big/ \sqrt{[(1-\rho)\sum Wi^2 + \rho\ (\sum Wi^2)]}$$

where:

- Xi = GAS score.
- Wi = weight of each GAS scale (2/1).
- ρ = 0.3 correlation coefficient between GAS scores [26, 27].

We also used a binary GAS which separates good functional results (GAS ≥ 0) from poor ones (GAS < 0).

Clinical examination was classical, performed by the investigator, assessing ankle range of motion, transfer function, use of external devices and analytic assessment of the foot.

Data pathway

Data was collected on a computer, saved locally, rendered anonymous, and transferred on portable hard drives to the Borelli Center (UMR 9010 CNRS - Paris-Saclay University – Paris Cité University – SSA – INSERM) following standard MR001.

Spatiotemporal gait parameters

We used the semiogram as described in [23], applicated with an automated gait events segmentation algorithm [22]. The calculation methods for each parameter were derived from the literature and are detailed in a previous paper [23]. In addition, with average speed which is shown separately, the seven semiological criteria used were:

1. Springiness: refers to gait rhythmicity.
2. Smoothness: refers to gait continuousness or non-intermittency [20, 25, 28–31].
3. Steadiness: refers to gait regularity.
4. Sturdiness: refers to gait amplitude.
5. Stability: refers to gait balance [32].
6. Symmetry: refers to right/left concordance during gait [33–36].
7. Synchronization: refers to inter-limb coordination during gait.

The visual rendering of the semiogram enables instant visual analysis of the patient's gait, as we show in the results section. To determine whether a significant improvement was observed, we used the area of the semiogram using average speed as a coefficient comparing M0 to M6. Since the calculation of the area is sensitive to the scale used and the order of parameters around the diagram, we established the previously mentioned order for a Z-score value ranging from 2 to -20. Therefore, the formula for the area of the semiogram weighted by average speed is as follows:

$$\mathcal{A}_{\text{semio}} = 0.5 * (20 + Z_{\text{speed}}) \cdot \sum_{i=1}^{7} (20 + Z_i) \cdot (20 + Z_{i+1})$$

where:

- Z_{speed} represents the Z-score of average speed
- For i ranging from 1 to 7, Z_i represents the Z-score of the i-th parameter
- Z_8 represents the Z-score of the first parameter ($Z_8 = Z_1$)

Statistics

Given that this study marked the inaugural application of the semiogram in assessing patients with post-stroke SEVF occurrence both before and after surgery, the sample size was determined by the progression of consultations conducted at the center within a predefined timeframe, rather than by a prior power analysis. Initial findings were explored through two-sided non-parametric tests with a significance threshold of 0.05. Regarding the semiogram evaluation, individual gait patterns were analyzed separately for each patient at the M0 and M6 timepoints, considering gait with and without shoes.

The quality of the walking event detection algorithm was previously validated in a similar cohort [19], and the authors of the article visually verified the segmentation of each walking trial to ensure detection consistency. At each evaluation date, patients walked both with and without shoes. Recognizing walking test with or without shoes as two distinct ways of evaluating walking, a test-retest design was employed to assess the measurement variability between the two conditions. The relative reliability was determined using the ICC (3,1), which gauges the consistency of single measurements while assuming that the variability arises from systematic bias.

To assess the performance of the semiogram in surgical operations among post-stroke SEVF patients, multiple tests were conducted. At the semiological level, the relationship between discrete GAS T scores and alterations in each criterion between M0 and M6 was initially investigated via the Kruskal-Wallis test. A Kendall's rank test was also applied, categorizing patients into two groups: those exhibiting clinical improvement (GAS T score ≥ 50) and those without such improvement (GAS T score < 50). As the walking tests were administered under conditions reflecting usual patient gait, albeit with limited assistance, some patients experienced reduced walking aid between M0 and M6, which introduced complexity to the analysis. To enhance result interpretation, non-parametric Wilcoxon-Mann-Whitney tests were performed to compare patients who reduced walking assistance with the remaining group.

At the comprehensive semiogram level, analogous tests were executed, encompassing the area weighted by average speed, as previously elucidated. To assess the relevance of the semiogram as a whole, an analysis of the relative evolution of the weighted semiogram area between M0 and M6 in the population that perceived a benefit from the operation (GAS T score ≥ 50) was conducted. This analysis differentiated between patients who used this benefit to reduce their need for walking assistance and those who continued to use the same walking aid at both evaluations.

Lastly, a thorough visual portrayal of semiograms and their evolution between M0 and M6 was conducted by the clinician, with the objective of understanding their utility on both individual and clinical fronts.

Results

Functional results

We included 22 patients operated for post-stroke SEVF, two of them were lost of follow up. Demographic and clinical data are shown in Table 1.

20 patients had a gait analysis preoperatively and at 6 months postoperatively. GAS assessment was performed at the last follow-up at 6 months. Table 1 summarizes all the surgical procedures performed. The GAS objectives, their results and the walking aid Necessity before and after surgery are shown in Table 2. For the T score calculation, GAS objective 1 had a weighting of 2 and objective 2 had no weighting. Considering binary GAS 90% (18/20) patients had a GAS improvement and 50% (10/20) had an improvement in walking technique as evidenced by the cessation of the use of a walking aid. Regarding the adverse events, one patient had lateral scar disunion after Split Anterior Tibial Tendon Transfer (SPLATT) treated by directed wound healing. Two patients had a recurrence of the deformation at 6 months, one of the equinus only probably due to insufficient post-operative rehabilitation, and one of dynamic varus by rupture of the SPLATT treated by transfer of the TA on the third metatarsus with good result.

Table 1 Patients characteristics and type of surgery

Patients	Sex	Age	Side	Surgical procedure
1	M	54	RIGHT	SPLATT + TL (Achille + fdl)
2	M	29	LEFT	SPLATT + TL (gastroc + fdl)
3	M	65	LEFT	SPLATT + TL (gastroc)
4	M	66	LEFT	STN (sol + TP) + TT (TA)
5	F	39	LEFT	SPLATT + TL (gastroc)
6	M	47	RIGHT	SPLATT + TL (gastroc + fdl)
7	F	52	LEFT	STN (sol) + SPLATT + TL (gastroc + fdl)
8	F	52	RIGHT	STN (sol) + SPLATT + TL (achille + fdl)
9	F	50	LEFT	TL (gastroc + fdl)
10	F	56	LEFT	SPLATT + TL (Achille + fdl)
11	F	67	LEFT	TL (gastroc + fdl)
12	F	54	LEFT	TL (gastroc + fdl)
13	F	51	RIGHT	SPLATT + TL (Achille + fdl)
14	F	51	RIGHT	SPLATT + TL (Achille + fdl)
15	F	80	LEFT	TL (achille + Fdl + fhl)
16	F	25	RIGHT	SPLATT + TL (gastroc + fdl)
17	F	72	RIGHT	SPLATT + TL (Achille + fdl)
18	M	29	RIGHT	STN (sol, TP) + TL (fdl/fhl)
19	M	41	LEFT	SPLATT + TL (Achille + fdl)
20	M	67	RIGHT	STN (sol) + SPLATT + TL (gastroc + fdl)

STN: selective tibial neurotomy; sol: soleus; tp: tibialis posterior; fhl: flexor hallucis longus; TL: tendon lengthening procedure; gastroc: gastrocnemius; fdl: flexor digitorum longus; achille: achilles tendon; splatt: split anterior tibial tendon transfer

Global semiogram analysis

The number of examinations obtained was 72 out of the 80 expected, as a number of patients were unable to perform a barefoot passage, and some were too tired after the first passage. Automatic gait events detection has been realized in another study and compared to GaitRite [22]. We assess the correspondence between barefoot and "with shoes" tests during the same sessions to evaluate an Intra-session intraclass correlation coefficients (ICCs) for speed and the seven criteria of the semiogram as shown in Fig. 1.

Regarding the comparison between groups with and without changes in walking assistance, no significant differences were found in the improvement of any of the criteria between M0 and M6. Figure 2 in the article presents the distribution within the cohort between the groups. A trend favoring the group with no change in walking assistance appears to be emerging but is not statistically significant. The average speed presented in Fig. 2 increased by +0.17 (sd = 0.63) in patients with functional improvement and technical change, and by +0.27 (sd = 0.50) in the group without technical change. In patients with an unfavorable outcome (GAS T score < 50), it decreased by -0.36 -0.46 and −0.24.

Considering the semiogram, the measurement of the area weighted by average speed demonstrated very good reproducibility (ICC(1, 3) = 0.80, Fig. 3A). In the group with a positive functional outcome (GAS T score ≥ 50), the change in the area shown in Fig. 3B was +9.5%, sd = 27.5% for the group with modification of walking aid, and +15.4%, sd = 28% in the group without change of walking aid. For the 3 experiences (2 patients) with unfavorable results, the area under the curve changed by +2.3%, -10.2% and −9.5%. The removal of a walking aid

Table 2 Functional objectives, GAS results and walking aids modification 6 months after surgery

Objective GAS 1	Objective GAS 2	GAS 1	GAS 2	T score M6	WA reduction	WA before surgery	WA after surgery
Crutch	Walking barefoot	1	2	63,3	1	AFO/crutch	None
Stability	Lift orthosis	2	0	63,3	1	AFO	None
Walking barefoot	Lift orthosis	-1	-1	40	0	Tripod / AFO	Tripod / AFO
Walking barefoot	Lift orthosis	0	0	50	0	Tripod / AFO	Tripod / AFO
Crutch	Walking barefoot	1	1	60	1	Tripod / AFO	None
Stability	Walking barefoot	1	0	56,7	1	Tripod	None
Walking barefoot	Stability	0	1	53,3	0	Crutch	None
Stability	Crutch	0	0	50	1	Tripod	None
Toe claws	Smoothness	0	1	53,3	0	Crutch	Crutch
Shoes	Metatarsalgia	0	1	53,3	0	Crutch / AFO	Crutch
Knee Flessum	Walk	0	-1	50	1	RW	Crutch
Stability	Smoothness	0	0	50	0	None	None
Douleur	Walking barefoot	0	0	50	0	None	None
Stability	Walking barefoot	0	0	50	1	Tripod AFO	None
Stability	Crutch	0	0	50	1	Tripod	Crutch
Stability	Crutch	1	0	56,7	1	Tripod / AFO	Crutch
Endurance	Lift orthosis	1	0	56, 7	0	Tripod / AFO	Tripod
Flat foot	Smoothness	0	0	50	0	None	None
Stability	Flat foot	0	-1	46, 7	1	Tripod	Crutch
Walking barefoot	Stability	0	0	50	0	Crutch	Crutch

GAS : Goal Attainment Scale, WA : Walking Aids, AFO : Ankle Foot Orthosis

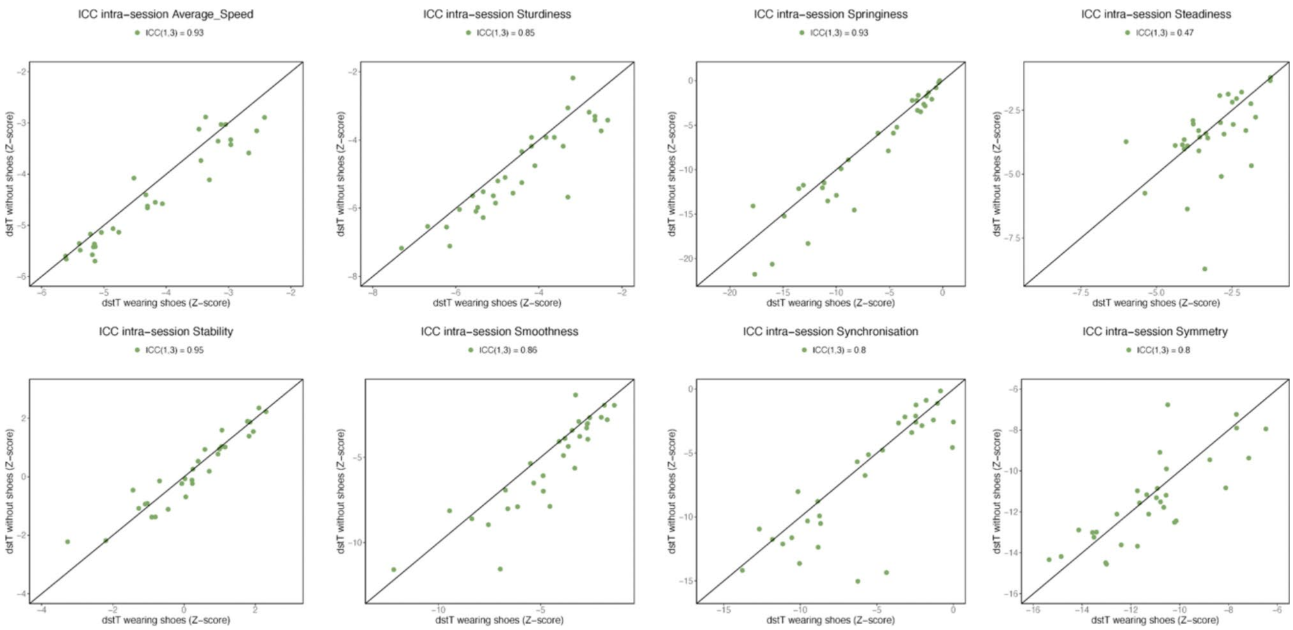

Fig. 1 Assessment of the correspondence between barefoot and "with shoes" tests during the same sessions to evaluate an Intra-session intraclass correlation coefficients (ICCs) for speed and the seven criteria of the semiogram: sturdiness, stability, synchronization, smoothness, symmetry

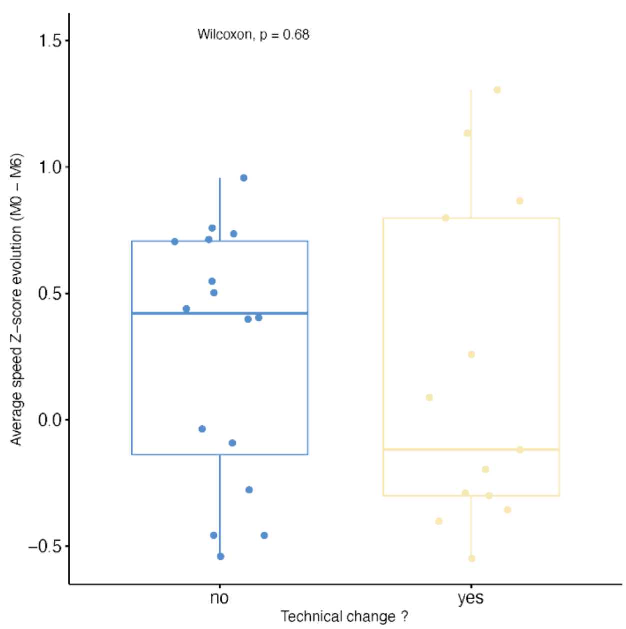

Fig. 2 Average speed Z score evolution between M0 and M6 in groups with and without technical change

can be considered as an objective functional improvement, which explains why in the group without change of walking aid the evolution of the area is more marked than in the group with change, confirming the good sensitivity of semiogram. The use of semiogram area as the main criterion showed no significant result, but an overall trend comparable to the evolution of GAS.

Individual analysis of the semiogram

Patients with a poor clinical outcome showed a decrease in their overall semiogram score. For patients who had a significant improvement in their gait characterized by the cessation of use of a walking aid, a comparable semiogram was considered to represent an improvement. We have detailed three examples of results in Fig. 4. On Fig. 4A, the patient's walking was generally good without technical aids prior to surgery. There was a good improvement in his gait, in line with the GAS score. Figure 4B shows the results of a patient with a recurrence of transplant rupture, showing no improvement in gait and even deterioration in some parameters. Stability is paradoxically excellent, as the patient has a very slow gait using a tripod cane. Figure 4C shows a very similar pre- and postoperative appearance, however the patient stopped using a valve and orthopedic shoes following the procedure. This clearly shows that there was no fundamental change in gait pattern, but better stability in both barefoot and commercially available shoes, resulting in significant functional improvement.

Discussion

Functional results

The functional results of this cohort of post stroke SEVF treated surgically with a global neuro-orthopedic approach combining nerve and tendon interventions are in line with those reported in the literature [1, 6, 37, 38]. As reported by Salga et al. [4] we believe that that this specific approach should be carried out by specialized teams performing the full range of available procedures,

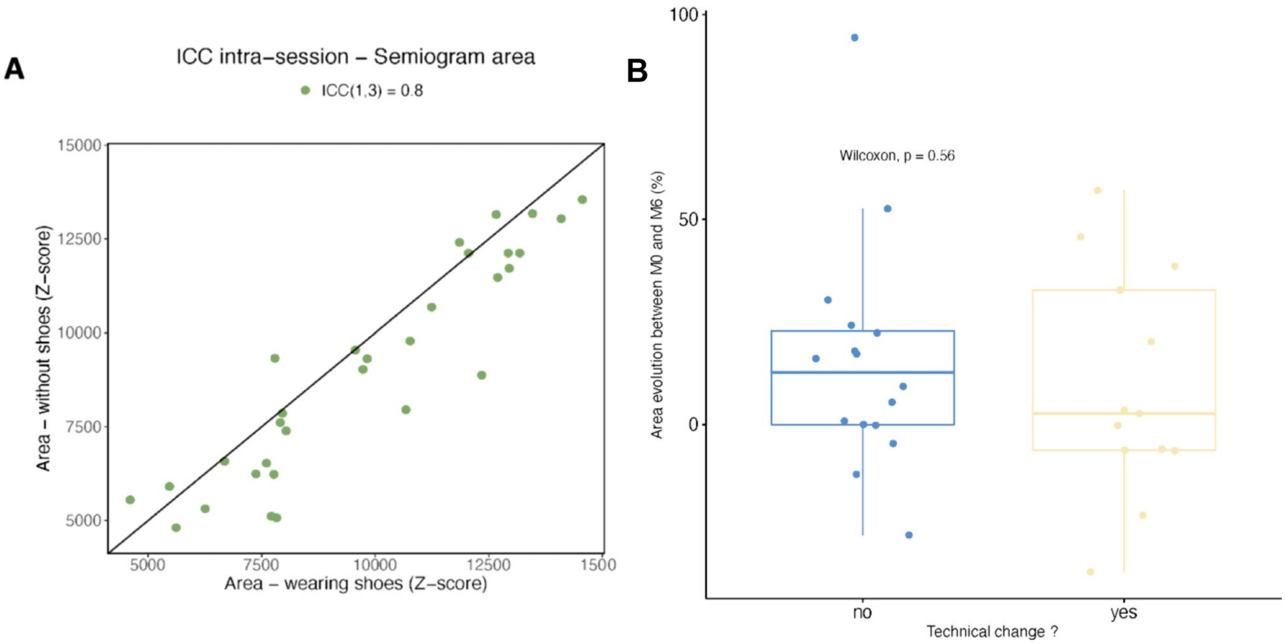

Fig. 3 **A**. Intraclass correlation coefficients for Semiogram area between barefoot and "with shoes" tests **B**. Area evolution between M0 and M6 in groups with and without technical change. There was a greater increase in the area of the semiogram in the group without technical change than in the group with technical change

rather than by separate neurosurgical or orthopedic teams [2, 7, 39].

Evaluation methods in SEVF surgery

As previously shown in a literature review [8], the impact on patients' overall gait is very difficult to quantify clinicall, making it difficult to establish a standardized method for evaluating the efficacy of SEVF surgery after stroke. Most of the scales lack specificity, and the most promising option appears to be the Goal Attainment Scale [6, 10, 40, 41]. GAS shows good sensitivity and specificity for assessing the functional impact of a treatment. However, because it is assessed at precise points in time, as in this case at M0 and M6, it does not allow quantified and progressive dynamic monitoring of gait evolution. It only has 5 different levels, which only allows a fairly binary analysis of the result as favorable or unfavorable. Furthermore, a recurring criticism of GAS lies in the ability of teams to set objectives in a way that is adapted so as not to distort results [10]. If these various reasons are in favor of a standardized automated gait analysis enabling finer-grained monitoring, they also complicate the validation of a new tool, as it will not be possible to highlight a correlation as is done in MS, for example, with the EDSS score [17, 23].

Interest and limitations of the semiogram

The use of IMUs is growing all the time. They show excellent reliability for monitoring the activity of healthy subjects [42], and are increasingly being used to monitor patients with neurological pathologies. However, the more degraded the gait, the more complicated it becomes to use automated gait event detection and analysis tools. Although studied in hemiplegic patients, IMUs had not previously been used perioperatively [14, 19, 20, 43, 44]. This study validated the feasibility of gait analysis by IMU in patients undergoing post-stroke SEVF surgery. This offers major prospects for improving the follow-up of hemiplegic post-stroke patients. Conventional Quantitative Gait analysis is often difficult to perform in routine clinical practice and is mainly used to plan interventions. This makes it difficult to simplify and quantify, for example, to evaluate correlation with another variable or to assess overall trends. To improve practices, an automated, quantified and objective assessment seems essential, and is now possible with this cost-effective technique that can easily be deployed in clinics. While some teams have chosen to focus on a single criterion such as smoothness [17], our study raises the point that no single gait criterion is perfectly sufficient. The utilization of a semiogram that integrates several gait analysis parameters appears to be a more nuanced approach for assessing the evolution of gait at the individual level. This multi-parameter approach has already been used by teams such as Del din et al. and Ben Mansour et al. [45–47]. The interest of the semiogram lies in its close relationship with the clinical examination moreover this tool has also been made available online to any team wishing to use it. It can therefore be used widely and reproducibly [48]. All algorithms can be accessed and used online at https://www.ipol.im/. The use of 7 different clinical

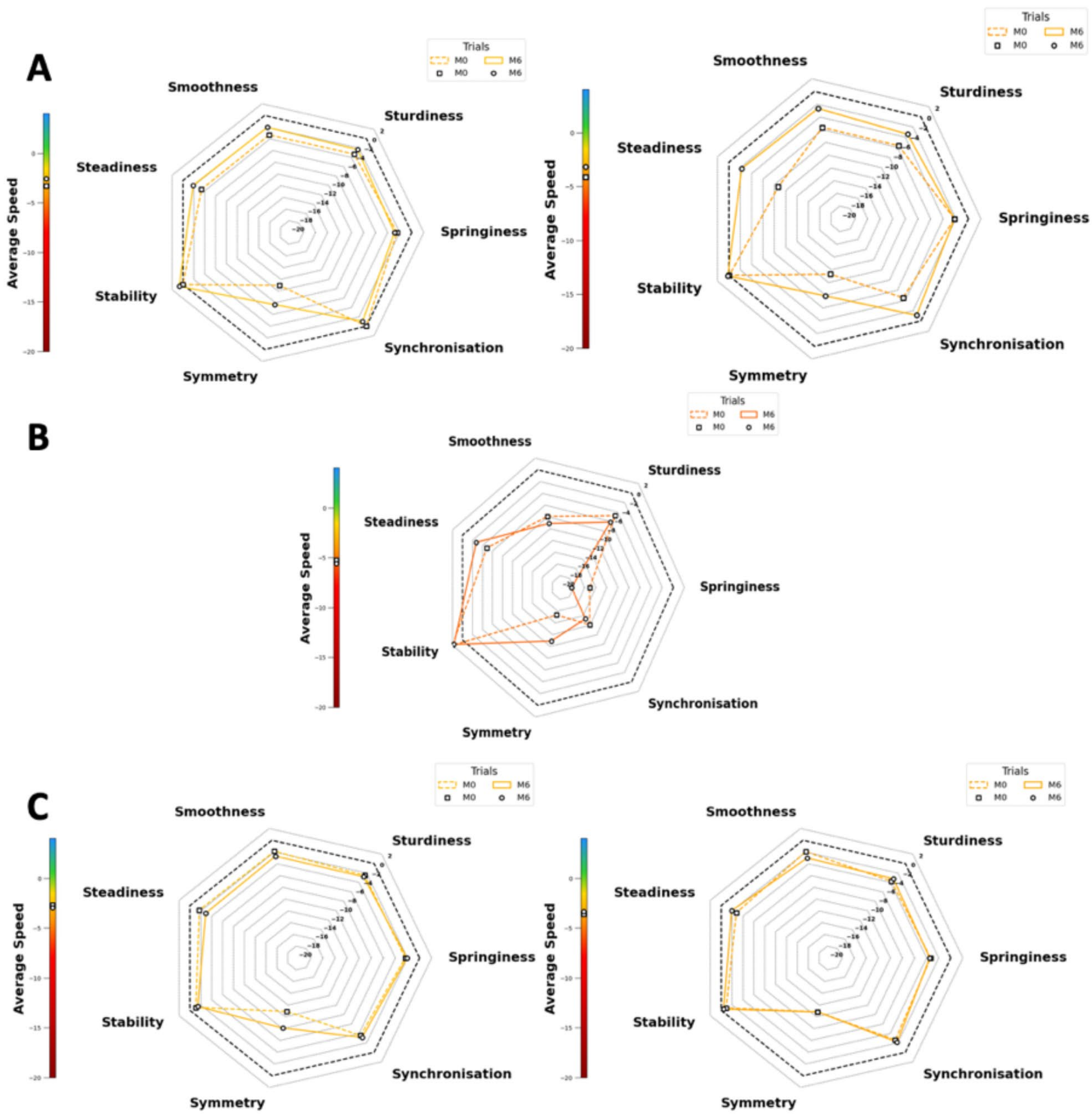

Fig. 4 **A**. Pre- and post-operative semiograms showing improvement in global walk (with shoes on the left and barefoot on the right). The patient had no walking aid pre- and post-operative and GAS 0/0. **B**. Pre- and post-operative semiograms showing no improvement in global walk. The patient had a GAS = -1. He was walking with a tripod cane before and after explaining the very good stability score. **C**. Pre- and post-operative semiograms showing no significative improvement in a patient with a GAS = 1–2 but who had orthopedic shoes and walking stick before surgery and no walking aids after (with shoes on the left and barefoot on the right)

parameters seemed relevant for the evaluation of patients included in this study. However, a more specific evaluation of variations in these parameters on larger cohorts would be interesting [23]. Our results in this new population showed that parameter and criterion calculations are reproducible. Thus, the semiogram appears to be an easily accessible and reproducible complement that can be used to compare new surgical techniques with greater precision than a simple functional analysis [12]. The main limitations of the semiogram in our practice are mainly linked to the significant variation in parameters depending on the pathologies studied. As a result, the reading scale may need to be adapted to highlight variations. In addition, it is a graphic tool designed to facilitate reading for the clinician by integrating a wealth of information. The area of the semiogram the area with a general coefficient for speed corresponds to the clinician's visual rendering since the comparison between the areas of the ploygons is made immediately and the addition of the color code for speed gives an overall appreciation of the gait. The use of polygon area in this study represents one solution, but other possibilities should be investigated. Indeed It allows overall quantitative evaluation, but does not give a fine semiological reading that a semiogram can provide.

IMU and SEVF

The first step was to obtain efficient market event detection. We have subsequently shown in this study that the semiogram can be used in the postoperative analysis of the post-stroke SEVF. The difficulty in analyzing the postoperative result lies in the lack of effective tools available. Because of their fundamental difference in use, GAS and semiogram do not show any statistical correlation, although their evolution is similar overall. However, their use is complementary. GAS only gives a definitive result at a distance but does not allow us to monitor the progressive evolution of gait postoperatively, or to assess even minimal changes in gait. On the other hand, the semiogram has an objective and quantitative character that may be useful when comparing two techniques or two therapies, such as a motor block and the efficacy of an intervention [49], or an innovative surgical procedure [12]. It would also be interesting to use it in the evaluation of temporary therapies such as botulinum toxin injections. This would make it possible to assess the period of efficacy and any recurrence of functional discomfort. This would enable us to adapt the therapies used and their temporality to the patient's needs. It would also make it possible to increase the number of patients analyzed, to increase the power of the statistical tests used. Finally, an untested utility of the semiogram could be to enable patients to monitor their gait, during rehabilitation for example, which would enable them to directly observe any improvement or deterioration. Indeed the major advantage of the semiogram is that it enables prospective follow-up, which is not possible with GAS, and can be used to monitor patients, notably by alerting to unfavorable evolution of at least one of the criteria.

Limits and perspective

Although this study is prospective and monocentric, one of its main limitations is the small number of patients included and the relatively short follow-up period. In order to refine and optimize the use of the semiogram in post-stroke hemiplegic patients, it would be interesting to follow larger cohorts in order, in particular, to compare the results of motor blocks with those of surgery [50, 51] or toxin for which semiogram could be of real interest in individual longitudinal monitoring [52].

Conclusion

IMUs appear to be a promising solution for the assessment of post-stroke hemiplegic patients who have undergone SEVF surgery. They can provide a quantified, objective, reliable in individual longitudinal follow up automated gait analysis solution for routine clinical use. The use of IMU in routine clinical practice should make it possible to standardize and make objective and quantified the post-operative assessment of patients, which is currently based solely on subjective scales.

Author contributions

NE and CV conceived the study, participated in the analysis, participated in the data acquisition, and wrote the manuscript. AM, PD and MM conceived the study and participated in the data acquisition. AV, CV, CD, Alain M, AJ, LM, LG participated in the data acquisition. LO, SJ and NV conceived the study and edited the manuscript. DR conceived the study, participated in the data acquisition, and edited the manuscript. All authors contributed to the refinement of the study protocol and approved the final manuscript.

Funding

No funding was received to conduct this research.

Data availability

The healthy subject's dataset and the online demonstration of the semiogram are accessible at the following address: https://www.ipol.im/.

Declarations

Ethics approval and consent to participate

The studies involving humans were approved by Protection des Personnes Nord Ouest III (ID RCB: 2017-A01538-45). The study was conducted in accordance with the local legislation and institutional requirements. The participants provided their written informed consent to participate in this study.

Consent for publication

All authors have given their consent for the publication of this study.

Competing interests

The authors declare no competing interests.

Author details

[1]Service de Chirurgie Orthopédique, Traumatologique et Réparatrice des Membres, Service de Santé des Armées, HIA Percy, Clamart F-92140, France
[2]Université Paris Cité, Université Paris Saclay, ENS Paris Saclay, CNRS, SSA, INSERM, Centre Borelli, Paris, France
[3]CRF Les Trois Soleils, Médecine Physique et de Réadaptation, Unité de Rééducation Neurologique, Boissise-Le-Roi, France
[4]Université Paris Saclay, Université Paris Cité, ENS Paris Saclay, CNRS, SSA, INSERM, Centre Borelli, Gif-sur-Yvette F-91190, France
[5]Service de Chirurgie Orthopédique, Hôpital Raymond Poincaré, APHP, Garches, France
[6]Service de Médecine Physique et Réadaptation, HIA Percy, Clamart F-92140, France
[7]Service de Neurologie, Service de Santé des Armées, HIA Percy, 101 Avenue Henri Barbusse, Clamart F-92140, France
[8]École du Val-de-Grâce, Service de Santé des Armées, Paris F-75005, France

Received: 25 September 2023 / Accepted: 9 September 2024
Published online: 16 October 2024

References

1. Deltombe T, Gavray T, Van Roy O, Wautier D, Gustin T. Medico-surgical management of the spastic equinovarus foot deformity in adults: a retrospective series of 622 patients. J Int Soc Phys Rehabil Med. 2022;5:156.
2. Genêt F, Denormandie P, Keenan MA. Orthopaedic surgery for patients with central nervous system lesions: concepts and techniques. Ann Phys Rehabil Med. 2019;62:225–33.
3. Verdié C, Daviet JC, Borie MJ, Popielarz S, Munoz M, Salle JY et al. [Epidemiology of pes varus and/or equinus one year after a first cerebral hemisphere stroke: apropos of a cohort of 86 patients]. Ann Readapt Med Phys [Internet]. 2004 [cited 2024 Apr 23];47:81–6. https://pubmed.ncbi.nlm.nih.gov/15013602/
4. Salga M, Gatin L, Deltombe T, Gustin T, Carda S, Marque P et al. International recommendations to manage post-stroke Equinovarus Foot deformity validated by a panel of experts using DELPHI. Arch Phys Med Rehabil [Internet]. 2022 [cited 2022 Aug 30]; http://www.ncbi.nlm.nih.gov/pubmed/36030892
5. Chan B, Salib M, Faggianelli F, Marque P, Cormier C, Gasq D. Selection criteria for surgical correction of equinovarus foot in adults with brain damage: A systematic scoping review. Ann Phys Rehabil Med [Internet]. 2023 [cited 2023 Aug 28];66. https://pubmed.ncbi.nlm.nih.gov/35240327/
6. Deltombe T, Gilliaux M, Peret F, Leeuwerck M, Wautier D, Hanson P et al. Effect of the neuro-orthopedic surgery for spastic equinovarus foot after stroke: a prospective longitudinal study based on a goal-centered approach. Eur J Phys Rehabil Med [Internet]. 2018 [cited 2019 Apr 6];54:853–9. http://www.ncbi.nlm.nih.gov/pubmed/29904043
7. Allart E, Sturbois-Nachef N, Salga M, Rosselin C, Gatin L, Genet F. Neuro-orthopaedic Surgery for Equinovarus Foot Deformity in Adults: a Narrative Review. J Foot Ankle Surg. 2021;in press.
8. de l'Escalopier N, Voisard C, Michaud M, Moreau A, Jung S, Tervil B et al. Evaluation methods to assess the efficacy of equinovarus foot surgery on the gait of post-stroke hemiplegic patients: a literature review. Front Neurol. 2022;13.
9. Turner-Stokes L, Williams H, Johnson J. Goal attainment scaling: does it provide added value as a person-centred measure for evaluation of outcome in neurorehabilitation following acquired brain injury? J Rehabil Med [Internet]. 2009 [cited 2021 Jun 15];41:528–35. http://www.ncbi.nlm.nih.gov/pubmed/19543663
10. Krasny-Pacini A, Hiebel J, Pauly F, Godon S, Chevignard M. Goal Attainment Scaling in rehabilitation: A literature-based update. Ann Phys Rehabil Med [Internet]. 2013;56:212–30. https://doi.org/10.1016/j.rehab.2013.02.002
11. Dauleac C, Luaute J, Rode G, Afif A, Sindou M, Mertens P. Evaluation of Selective Tibial Neurotomy for the Spastic Foot Treatment Using a Personal Goal-Centered Approach: A 1-Year Cohort Study. Neurosurgery [Internet]. 2023 [cited 2023 Jun 5];92:862–9. https://pubmed.ncbi.nlm.nih.gov/36700737/
12. Diner C, Mathieu L, Pfister G, Mourtialon R, Denormandie P, de l'Escalopier N. Nerve transfer in the spastic equino varus foot: Anatomical feasibility study. Foot Ankle Surg [Internet]. 2023 [cited 2023 May 1]; https://pubmed.ncbi.nlm.nih.gov/37095035/
13. Polhemus A, Ortiz LD, Brittain G, Chynkiamis N, Salis F, Gaßner H et al. Walking on common ground: a cross-disciplinary scoping review on the clinical utility of digital mobility outcomes. Npj Digit Med. 2021;4.
14. Yang S, Zhang J-T, Novak AC, Brouwer B, Li Q. Estimation of spatio-temporal parameters for post-stroke hemiparetic gait using inertial sensors. Gait Posture [Internet]. 2013 [cited 2019 Apr 4];37:354–8. http://www.ncbi.nlm.nih.gov/pubmed/23000235
15. Pau M, Mandaresu S, Pilloni G, Porta M, Coghe G, Marrosu MG et al. Smoothness of gait detects early alterations of walking in persons with multiple sclerosis without disability. Gait Posture [Internet]. 2017 [cited 2023 Apr 24];58:307–9. https://pubmed.ncbi.nlm.nih.gov/28858779/
16. Vienne-Jumeau A, Quijoux F, Vidal P-P, Ricard D. Wearable inertial sensors provide reliable biomarkers of disease severity in multiple sclerosis: A systematic review and meta-analysis. Ann Phys Rehabil Med [Internet]. 2020 [cited 2022 Feb 15];63:138–47. http://www.ncbi.nlm.nih.gov/pubmed/31421274
17. Bois A, Tervil B, Moreau A, Vienne-Jumeau A, Ricard D, Oudre L. A topological data analysis-based method for gait signals with an application to the study of multiple sclerosis. PLoS One [Internet]. 2022 [cited 2023 May 26];17. https://pubmed.ncbi.nlm.nih.gov/35560328/
18. Ibrahim AA, Küderle A, Gaßner H, Klucken J, Eskofier BM, Kluge F. Inertial sensor-based gait parameters reflect patient-reported fatigue in multiple sclerosis. J Neuroeng Rehabil [Internet]. 2020 [cited 2023 Apr 25];17. https://pubmed.ncbi.nlm.nih.gov/33339530/
19. Buckley C, Micó-Amigo ME, Dunne-Willows M, Godfrey A, Hickey A, Lord S, et al. Gait asymmetry post-stroke: determining valid and reliable methods using a single accelerometer located on the trunk. Sens (Switzerland). 2020;20:1–17.
20. do Vale Garcia F, da Cunha MJ, Schuch CP, Schifino GP, Balbinot G, Pagnussat AS. Movement smoothness in chronic post-stroke individuals walking in an outdoor environment-A cross-sectional study using IMU sensors. PLoS One [Internet]. 2021;16:1–18. https://doi.org/10.1371/journal.pone.0250100
21. Schwarz A, Al-Haj Husain A, Einaudi L, Thürlimann E, Läderach J, Awai Easthope C et al. Reliability and Validity of a Wearable Sensing System and Online Gait Analysis Report in Persons after Stroke. Sensors (Basel) [Internet]. 2023 [cited 2023 Jun 29];23. https://pubmed.ncbi.nlm.nih.gov/36679424/
22. Voisard C, de l'Escalopier N, Ricard D, Oudre L. Automatic Gait Events Detection with Inertial Measurement Units: Healthy Subjects and Moderate to Severe Impaired Patients. J Neuroeng Rehabil. 2023;under review.
23. Voisard C, de l'Escalopier N, Vienne-Jumeau A, Moreau A, Quijoux F, Bompaire F et al. Innovative multidimensional gait evaluation using IMU in multiple sclerosis: introducing the semiogram. Front Neurol [Internet]. 2023 [cited 2023 Oct 6];14. https://pubmed.ncbi.nlm.nih.gov/37780706/
24. Vienne A, Barrois RP, Buffat S, Ricard D, Vidal PP. Inertial sensors to assess gait quality in patients with neurological disorders: a systematic review of technical and analytical challenges. Front Psychol. 2017;8:1–12.
25. Melendez-Calderon A, Shirota C, Balasubramanian S. Estimating Movement Smoothness from Inertial Measurement Units. Front Bioeng Biotechnol. 2021;8:1–16.
26. Krasny-pacini A, Hiebel J, Pauly F, Godon S, Chevignard M, Finlayson H et al. Goal Attainment Scaling in rehabilitation: A literature-based update. Ann Phys Rehabil Med [Internet]. 2013;56:1–14. https://doi.org/10.1016/j.rehab.2013.02.002
27. Kiresuk TJ, Sherman RE. Goal attainment scaling: A general method for evaluating comprehensive community mental health programs. Community Ment Health J [Internet]. 1968 [cited 2021 Jun 15];4:443–53. http://www.ncbi.nlm.nih.gov/pubmed/24185570
28. Balasubramanian S, Melendez-Calderon A, Roby-Brami A, Burdet E. On the analysis of movement smoothness. J Neuroeng Rehabil [Internet]. 2015;12:1–11. https://doi.org/10.1186/s12984-015-0090-9
29. Beck Y, Herman T, Brozgol M, Giladi N, Mirelman A, Hausdorff JM. SPARC: a new approach to quantifying gait smoothness in patients with Parkinson's disease. J Neuroeng Rehabil. 2018;15:1–9.
30. Pinto C, Schuch CP, Balbinot G, Salazar AP, Hennig EM, Kleiner AFR, et al. Movement smoothness during a functional mobility task in subjects with Parkinson's disease and freezing of gait - an analysis using inertial measurement units. J Neuroeng Rehabil. 2019;16:1–14.
31. Figueiredo AI, Balbinot G, Brauner FO, Schiavo A, Baptista RR, Pagnussat AS, et al. SPARC Metrics provide mobility smoothness Assessment in Oldest-Old with and without a history of Falls: a Case Control Study. Front Physiol. 2020;11:1–11.
32. Iosa M, Fusco A, Morone G, Pratesi L, Coiro P, Venturiero V et al. Assessment of upper-body dynamic stability during walking in patients with subacute stroke. J Rehabil Res Dev [Internet]. 2012 [cited 2023 Jun 29];49:439–50. https://pubmed.ncbi.nlm.nih.gov/22773202/
33. Pasciuto I, Bergamini E, Iosa M, Vannozzi G, Cappozzo A. Overcoming the limitations of the Harmonic Ratio for the reliable assessment of gait symmetry. J Biomech [Internet]. 2017 [cited 2023 Apr 26];53:84–9. https://pubmed.ncbi.nlm.nih.gov/28104246/
34. Gage H. Accelerographic analysis of human gait. Am Soc Mech Eng Biomech Monogr. 1967. pp. 137–52.
35. Bellanca JL, Lowry KA, VanSwearingen JM, Brach JS, Redfern MS. Harmonic ratios: a quantification of step to step symmetry. J Biomech [Internet]. 2013 [cited 2023 Apr 26];46:828–31. https://pubmed.ncbi.nlm.nih.gov/23317758/
36. Iijima H, Eguchi R, Aoyama T, Takahashi M. Trunk movement asymmetry associated with pain, disability, and quadriceps strength asymmetry in individuals with knee osteoarthritis: a cross-sectional study. Osteoarthr Cartil [Internet]. 2019 [cited 2023 Apr 26];27:248–56. https://pubmed.ncbi.nlm.nih.gov/30445222/
37. Mazzoli D, Giannotti E, Rambelli C, Zerbinati P, Galletti M, Mascioli F et al. Long-term effects on body functions, activity and participation of hemiplegic patients in equino varus foot deformity surgical correction followed by immediate rehabilitation. A prospective observational study. Top Stroke Rehabil [Internet]. 2019;26:518–22. https://doi.org/10.1080/10749357.2019.1642651
38. Giannotti E, Merlo A, Zerbinati P, Prati P, Masiero S, Mazzoli D. Safety and long-term effects on gait of hemiplegic patients in equinovarus foot deformity

surgical correction followed by immediate rehabilitation: a prospective observational study. Eur J Phys Rehabil Med. 2019;55:169–75.
39. Deltombe T, Wautier D, De Cloedt P, Fostier M, Gustin T. Assessment and treatment of spastic equinovarus foot after stroke: Guidance from the mont-godinne interdisciplinary group. J Rehabil Med. 2017;49:461–8.
40. Hanlan A, Mills P, Lipson R, Thompson D, Finlayson H. Interdisciplinary spasticity management clinic outcomes using the goal attainment scale: a retrospective chart review. J Rehabil Med. 2017;49:423–30.
41. Jung Y, Sim J, Park J, Kim J, Kim MY. Usefulness of goal attainment scaling in intensive stroke rehabilitation during the subacute stage. Ann Rehabil Med. 2020;44:181–94.
42. Kobsar D, Charlton JM, Tse CTF, Esculier JF, Graffos A, Krowchuk NM, et al. Validity and reliability of wearable inertial sensors in healthy adult walking: a systematic review and meta-analysis. J Neuroeng Rehabil. 2020;17:1–21.
43. Barrois RPM, Ricard D, Oudre L, Tlili L, Provost C, Vienne A, et al. Observational study of 180° turning strategies using inertial measurement units and fall risk in poststroke hemiparetic patients. Front Neurol. 2017;8:1–11.
44. Mizuike C, Ohgi S, Morita S. Analysis of stroke patient walking dynamics using a tri-axial accelerometer. Gait Posture. 2009;30:60–4.
45. Del Din S, Yarnall AJ, Lo BTR, Crabbe C, Rolinski M, Baig M. F., Hu, M. T., & Rochester L. Continuous real- world gait monitoring in idiopathic REM sleep behavior disorder. J Parkinsons Dis. 2019.
46. Del Din S, Elshehabi M, Galna B, Hobert MA, Warmerdam E, Suenkel U, et al. Gait analysis with wearables predicts conversion to parkinson disease. Ann Neurol. 2019;86:357–67.
47. Mansour K, Ben, Gorce P, Rezzoug N. The multifeature gait score: An accurate way to assess gait quality. PLoS One [Internet]. 2017;12:1–12. https://doi.org/10.1371/journal.pone.0185741
48. Voisard C, de l'Escalopier N, Moreau A, Vienne-Jumeau A, Ricard D, Oudre L. A Reference Data Set for the Study of Healthy Subject Gait with Inertial Measurements Units. Image Process Line [Internet]. 2023 [cited 2023 Aug 21]; https://www.ipol.im/pub/pre/497/
49. Buffenoir K, Rigoard P, Lefaucheur J-P, Filipetti P, Decq P. Lidocaine hyperselective motor blocks of the triceps surae nerves: role of the soleus versus gastrocnemius on triceps spasticity and predictive value of the soleus motor block on the result of selective tibial neurotomy. Am J Phys Med Rehabil [Internet]. 2008 [cited 2021 May 15];87:292–304. http://www.ncbi.nlm.nih.gov/pubmed/18356621
50. Khalil N, Chauvière C, Le Chapelain L, Guesdon H, Speyer E, Bouaziz H, et al. Plantar pressure displacement after anesthetic motor block and tibial nerve neurotomy in spastic equinovarus foot. J Rehabil Res Dev. 2016;53:219–28.
51. Bollens B, Gustin T, Stoquart G, Detrembleur C, Lejeune T, Deltombe T. A randomized controlled trial of selective neurotomy versus botulinum toxin for spastic equinovarus foot after stroke. Neurorehabil Neural Repair. 2013;27:695–703.
52. Bensmail D, Wissel J, Laffont I, Simon O, Scheschonka A, Flatau-Baqué B et al. Efficacy of incobotulinumtoxinA for the treatment of adult lower-limb post-stroke spasticity, including pes equinovarus. Ann Phys Rehabil Med [Internet]. 2021 [cited 2023 Aug 31];64. https://pubmed.ncbi.nlm.nih.gov/32294561/

Publisher's note

Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.