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Nicolas de L Escalopier

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Université Paris Cité

École doctorale Cerveau, Cognition, Comportement - ED 158

Centre Borelli

**Évaluation par InertialoLocographie de l'impact de la chirurgie du Pied Varus
Équin Spastique sur la démarche des patients hémiplegiques après Accident
Vasculaire Cérébral**

Par Nicolas de l'Escalopier

Thèse de doctorat de **Neuroscience**

Dirigée par Damien Ricard

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Devant un jury composé de :

Damien Ricard, PU-PH, Service de Santé des Armées, Directeur

Régine Le Bouquin Jeannès, PU, Université de Rennes, Rapporteur

Nasser Rezzoug, MCU, Université de Poitiers, Rapporteur

Joseph Bascou, Docteur, CERAH, Examineur

Laure Gatin, PHU, Université de Versailles Saint-Quentin-en-Yvelines, Examinatrice

Laurent Oudre, PU, ENS Paris-Saclay, Examineur

Stéphanie Pannier, PU-PH, Université Paris Cité, Examinatrice

Titre : Évaluation par InertialoLocographie de l'impact de la chirurgie du Pied Varus Équin Spastique sur la démarche des patients hémipariés après Accident Vasculaire Cérébral

Résumé: Le Pied Varus Équin spastique (PVES) est une des séquelles fréquentes et invalidantes des patients cérébrolésés (séquelle de traumatisme crânien ou d'AVC). La prise en charge chirurgicale neuro-orthopédique de cette complication s'avère souvent nécessaire en cas d'échec des mesures médicales. Celle-ci repose sur l'association de gestes tendineux et nerveux décidée en fonction de l'examen clinique pluri-disciplinaire du patient. Cette intervention ne normalise pas totalement la marche et il est cliniquement difficile d'apprécier le bénéfice de la chirurgie. Les échelles subjectives utilisées montrent des résultats globalement satisfaisants, cependant il n'existe pas d'outil satisfaisant, à ce jour, permettant une évaluation systématique objective et quantifiée de la marche globale en post opératoire. L'Analyse Quantifiée de la Marche a montré un intérêt notable dans cette indication, elle est cependant très peu utilisée car souvent difficile d'accès, et d'interprétation difficile. Notre laboratoire travaille depuis plusieurs années sur l'utilisation de mesures conjointes accélérométriques et gyroscopiques par des centrales de mesure inertielles dans l'analyse de la marche. Cette approche, appelée InertialoLocographie, repose sur l'utilisation de petits capteurs autonomes utilisables en consultation ou en ambulatoire, puis sur le traitement mathématique du signal brut issu de ces capteurs. Elle a montré une bonne efficacité dans l'analyse de la marche des patients victimes de maladies neurologiques. Notre objectif principal est d'évaluer l'efficacité de l'InertialoLocographie comme outil d'évaluation de l'impact de la chirurgie neuro-orthopédique du PVES sur la démarche des patients cérébrolésés.

Mots clefs : Pied Varus Équin, Centrales de mesures Inertielles, Analyse de la marche, hémiparié, AVC, Chirurgie neuro orthopédique

Title: Inertial measurement units to evaluate the effect of Equino Varus Foot surgery on poststroke hemiparetic patients gait.

Abstract : Spastic Equino Varus Foot (SVEF) is one of the most frequent and disabling sequelae after traumatic brain injury or stroke. Neuro-orthopedic surgical management of this complication is often necessary when medical measures fail. It is based on a combination of tendon and nerve interventions, decided on the basis of a multi-disciplinary clinical examination of the patient. This procedure does not completely normalize walking, and it is clinically difficult to assess the benefit of surgery. The subjective scales used show satisfactory results overall, but to date there is no satisfactory tool for systematic, objective and quantified assessment of overall gait postoperatively. Quantified Gait Analysis has shown considerable interest in this indication, but is rarely used, as it is often difficult to access and interpret. Our laboratory has been working for several years on the use of joint accelerometric and gyroscopic measurements by inertial measurement units in gait analysis. This approach is based on the use of small, autonomous sensors that can be used in consultation or outpatient settings, followed by mathematical processing of the raw signal from these sensors. It has proved highly effective in analyzing the gait of patients suffering from neurological diseases. Our main objective is to evaluate the effectiveness of inertial measurement units as a tool for assessing the impact of neuro-orthopedic surgery on PVES on the gait of brain-damaged patients.

Keywords : Spastic Equino Varus Foot, Inertial Measurement Unit, Gait Analysis, post-stroke hemiplegia, Neuro-orthopedic surgery

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« Aime et fais ce que tu veux ! » Saint Augustin

Liste des principales abréviations

AQM Analyse quantifiée de la Marche

AVC Accident Vasculaire Cérébral

GAS Goal Atteintment Scale

ILG InertialoLocographie

IMU Inertial Measurement Unit

MPR Médecine Physique et Réadaptation

PVES Pied Varus Équin Spastique

SEP Sclérose en Plaque

SPLATT Split Anterior Tibialis Transfer

TA Muscle Tibial Antérieur

TP Muscle Tibial Postérieur

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1. Introduction

1.1 Présentation du manuscrit

Il s'agit d'une thèse sur articles. Les parties rédactionnelles y sont rédigées en français, les articles sont eux présentés dans leur forme originale en anglais.

Une introduction générale présente la pathologie étudiée et intègre un premier article réalisant un état des lieux de l'évaluation post opératoire du Pied Varus Équin Spastique (PVES) post Accident Vasculaire Cérébral (AVC), avant d'introduire l'InertialoLocographie (ILG).

La partie Matériel et Méthodes présente la méthode d'acquisition et d'analyse des données de façon habituelle.

Les Résultats sont présentés sous formes d'articles déjà publiés ou en cours de publication. Le développement des résultats suit l'ordre logique de réalisation des articles. Nous débuterons par la segmentation du signal préliminaire indispensable à l'analyse des données. Puis le diagramme radar sera évalué sur une première cohorte d'apprentissage constituée de patients atteints de Sclérose en Plaque (SEP), avant d'être appliqué à la cohorte d'intérêt de ce travail les patients opérés d'un PVES post AVC.

La dernière partie consistera en une discussion générale sur l'apport de l'ILG dans l'évaluation post opératoire du PVES post AVC.

1.2 Le Pied Varus Équin spastique post AVC

1.2.1 Problématique clinique : Le pied varus équin post AVC

Le nombre de patients hémiplésiques survivant après un AVC ("Stroke--1989. Recommendations on stroke prevention, diagnosis, and therapy. Report of the WHO Task Force on Stroke and other Cerebrovascular Disorders.," 1989) est en augmentation constante (Maaijwee et al., 2014). La gestion au long cours des séquelles fonctionnelles consécutives à cet AVC est une problématique médico-chirurgicale complexe, à laquelle tentent de répondre

les équipes de Médecine Physique et Réadaptation (MPR), de Neurologie et de chirurgie spécialisées dans le handicap. L'hémiplégie ou hémiparésie qui constitue une des séquelles majeures des patients est à l'origine de tableaux cliniques variés. En effet, elle associe une paralysie dite flasque de certains muscles qui ne fonctionnent plus du tout, une atteinte partielle de certains muscles qui peuvent garder une commande volontaire ou se déclencher de façon syncinétique mais également une spasticité de certains muscles (Gracies, 2005). La spasticité est l'exagération du réflexe d'étirement musculaire au réflexe myotatique (Lance et al., 1980). Elle se traduit par deux symptômes : l'exagération des réflexes ostéotendineux et/ou les trépidations caractéristiques, déclenchées par l'examineur ou parfois par le mouvement actif lui-même ; et l'hypertonie musculaire en résistance à l'étirement passif du muscle, hypertonie dite « élastique » et dépendant de la vitesse d'étirement. L'association de muscles « hyperactifs » et de muscles paralysés est à l'origine de déformations dites neuro-orthopédiques invalidantes pour le patient. Parmi ces déformations, les patients victimes d'AVC développent classiquement un PVES (Figure 1). Cette déformation représente un challenge pour les équipes de rééducation (Keenan, 2011; Lawrence and Botte, 1994). La position en équin et inversion résulte d'un déséquilibre des forces s'exerçant sur l'arrière pied consécutif à une hypertonie musculaire associée à un réflexe ostéotendineux hyperactif. Schématiquement une hypertonie ou une rétraction des muscles de la loge postérieure est à l'origine de l'équin. Les gastrocnémiens, le soléaire ou l'ensemble du triceps peuvent être atteints. Le varus dynamique est le plus souvent lié à une hypertonie du Muscle Tibial Antérieur (TA) lors de la phase oscillante, mais le Muscle Tibial Postérieur (TP), ou l'Abducteur de l'Hallux peuvent également participer à la déformation. Il existe par ailleurs un déficit fréquent des éverseurs et des releveurs ayant une action valgissante que sont le Muscle Long Extenseur Des Orteils et le muscle Troisième Fibulaire. Cette position en varus équin pose des problèmes importants pour le port de chaussures, la position debout, les transferts et la marche. La plupart du temps des mesures non chirurgicales ne parviennent pas à traiter cette déformation de façon satisfaisante (Bensmail et al., 2021; Deltombe et al., 2022). La chirurgie neuro-orthopédique est reconnue comme étant un traitement efficace pour améliorer la position du pied en cas de pied varus équin d'origine spastique (Deltombe et al., 2018; Roper et al., 1978). La plupart du temps, une amélioration des scores fonctionnels, notamment de la Goal Attainment Scale (GAS) est obtenue (Khan et al.,

2008; Kiresuk and Sherman, 1968; Krasny-Pacini et al., 2013; Rockwood et al., 2003, 1997; Turner-Stokes, 2009; Turner-Stokes et al., 2009). Cette échelle est depuis plusieurs années la plus utilisée car elle est directement centrée sur le patient. Elle consiste en la définition en préopératoire d'objectifs fonctionnels précis définis par le patient et l'équipe chirurgicale. Cela permet une contractualisation de l'intervention. Les autres échelles fonctionnelles utilisées chez les patients victimes d'AVC ne sont pas spécifiques et aucune ne peut correspondre à l'attente précise des patients autour de l'intervention. Par ailleurs, la douleur et la spasticité du triceps sont améliorées, la mobilité de cheville, la vitesse de déplacement et la réduction de l'utilisation d'aides à la marche sont obtenues.



Figure 1 :

- A. Déformation en équin consécutif à une hypertonie ou une rétraction des muscles de la loge postérieure.
- B. Déformation en varus du pied droit lors du contact du pied au sol.
- C. Hypertonie du Tibial Antérieur (TA) à l'origine d'une déformation en varus dynamique lors de la phase oscillante

1.2.2 Stratégie chirurgicale actuelle

Le programme chirurgical pour cette déformation est adapté à l'examen clinique du patient réalisé en consultation pluridisciplinaire (Genêt et al., 2019). L'utilisation de blocs moteurs est d'une grande aide, notamment pour faire la part des choses entre hypertonie et rétraction (Buffenoir et al., 2008; Chan et al., 2023; Cormier et al., 2022). Les interventions proposées sont multiples et se divisent en trois catégories (Allart et al., 2021; Salga et al., 2022). Les interventions sur les nerfs, qui permettant de diminuer l'hypertonie lorsque le muscle n'est pas rétracté, il s'agit des neurotomies sélectives (Bollens et al., 2013, 2011; Caillet et al., n.d.; Dauleac et al., 2023, 2020; Decq et al., 2000; Deltombe et al., 2007; Deltombe and Gustin, 2010; Le Bocq et al., 2016; Rousseaux et al., 2009; Sindou and Mertens, 1988). Les gestes tendineux, qui peuvent consister en un allongement en cas de rétraction, ou en un transfert qui consiste à modifier la terminaison d'un tendon pour conserver une action motrice en modifiant son effet. Les gestes osseux qui sont nécessaires en cas de déformations fixées sont très rarement utilisés chez les patients victimes d'AVC, car les déformations restent réductibles très longtemps (Nonnekes et al., 2019). Si pendant longtemps les gestes nerveux avaient la préférence des équipes de neurochirurgie et les gestes osseux et tendineux celle des équipes d'orthopédie, la prise en charge actuelle est dite « neuro-orthopédique » et associe l'ensemble de ces gestes simultanément (Allart et al., 2021; Genêt et al., 2019; Salga et al., 2022). Schématiquement, pour l'équin qu'il soit isolé ou associé à un varus invalidant, les interventions réalisées sont la neurotomie des branches à destination des muscles hypertoniques, ainsi que l'allongement du tendon d'Achille ou de la lame des gastrocnémiens (Deltombe et al., 2018). Pour la prise en charge du varus dynamique, il existe de nombreuses techniques chirurgicales comme les plâtres successifs (Singer et al., 2003), le transfert du Muscle Ling Extenseur de l'hallux (Carda et al., 2010), le transfert antérieur du Muscle Long Fléchisseur des orteils (Morita et al., 1998, 1994), le transfert d'un hémi TP (Medina et al., 1989) ou le transfert du Muscle Court Fibulaire (Lord and Moati, 1979). Le transfert d'un hémi TA ou Split Anterior Tibialis Transfer (SPLATT) est l'intervention la plus réalisée dans ce contexte (Figure 2) (Edwards and Hsu, 1993; Hoffer et al., 1985; Vogt, 1998; Vogt et al., 2011). Le résultat de cette prise en charge chirurgicale du PVE post AVC montre une amélioration significative dans l'autonomie du patient, une amélioration de la marche, permet l'arrêt du

port de chaussures orthopédiques et le port de chaussures du commerce. Il s'agit d'une intervention fiable, reproductible et peu morbide. Elle permet un résultat stable à long terme sans récurrence de la déformation (Giannotti et al., 2019, 2016; Mazzoli et al., 2019; Reddy et al., 2008).

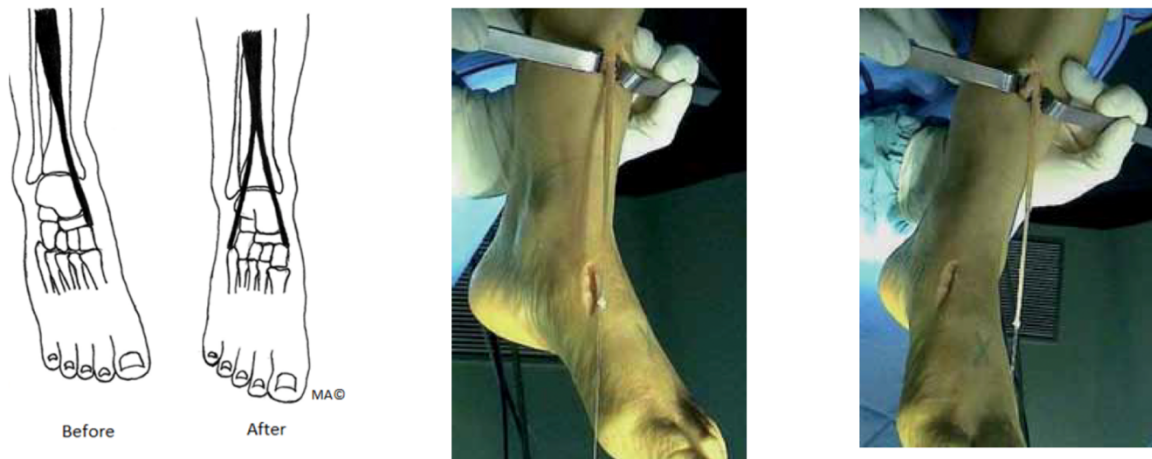


Figure 2 :

Split Anterior Tibialis Transfer

La moitié latérale du TA est désinsérée et transférée sur le court fibulaire via une mini incision.

La plupart du temps, le résultat obtenu en post opératoire est évalué par des échelles de qualité de Vie, la GAS, ou des mesures analytiques centrées sur la cheville et le pied. Il n'existe pas d'échelle fonctionnelle spécifique et les mesures instrumentales sont rarement utilisées en post opératoire.

1.3 L'évaluation post opératoire

1.3.1 Contexte évaluation post opératoire

De façon générale, l'évaluation du résultat post opératoire des interventions intéressant l'appareil locomoteur repose principalement sur une évaluation fonctionnelle subjective réalisée par le patient. Si cette évaluation trouve tout son sens à l'échelle individuelle, elle reste limitée dans la comparaison de plusieurs techniques chirurgicales ou dans l'analyse des échecs. Il existe un champ de recherche important dans l'analyse de l'impact de la chirurgie

des membres inférieurs sur la marche notamment. Si ces considérations sont applicables à la chirurgie orthopédique classique, la chirurgie « neuro-orthopédique » qui prend en charge les déformations de l'appareil locomoteur secondaire à des lésions du système nerveux central est encore plus concernée. L'évaluation des patients atteints de lésions nerveuses centrales est bien plus complexe d'une part parce que les schémas de marche sont pathologiques d'autre part en raison de l'atteinte locale orthopédique mais également en raison de modification de la commande elle-même. Une évaluation centrée sur l'articulation opérée trouve donc ses limites car une correction même réussie peut ne pas avoir d'effet ou un effet défavorable sur la marche globale du patient. Il est donc primordial d'évaluer la marche dans son ensemble et de ne pas se limiter à un examen analytique classique centré sur la déformation. A titre d'exemple un certain nombre de déformations sont qualifiées d'utiles et si elles sont corrigées peuvent être à l'origine d'une perte fonctionnelle pour le patient. Une difficulté majeure rencontrée dans l'évaluation des déformations spastiques de membres est représentée par leur caractère dynamique et non fixé. Lors de l'examen en chaîne ouverte, c'est-à-dire au lit du malade sans qu'il ne soit en charge, on peut avoir des mobilités conservées, alors qu'une déformation invalidante n'apparaît qu'en chaîne fermée lorsque le patient est en charge à la marche notamment. Cela est notamment lié à des contractions syncinétiques des muscles secondaires à la lésion cérébrale du patient. Pour cela une évaluation de la marche dans sa globalité paraît indispensable. Actuellement ce genre d'analyse est très difficile à obtenir en pratique clinique. L'analyse la plus rudimentaire consiste en l'évaluation de la marche par des observateurs indépendants sur des vidéos enregistrées en consultation (Decq et al., 2000; Delattre et al., 2021; Deltombe et al., 2018; Deltombe and Gustin, 2010). L'analyse quantifiée de la marche (AQM) par des marqueurs réfléchissants portés sur le corps représente l'outil de référence pour étudier les types de marche chez les humains (Fuller et al., 2002; Pinzur et al., 1986). L'analyse quantifiée de la marche apporte les données les plus précises pour évaluer cette chirurgie. Elle permet principalement d'améliorer le programme chirurgical des patients atteints de PVE spastique et permet de définir des stratégies plus homogènes entre opérateurs (Fuller et al., 2002). L'AQM a déjà été utilisée en post opératoire dans cette indication mais le plus souvent sans analyse fonctionnelle conjointe (Bollens et al., 2013; Buffenoir et al., 2008; Carda et al., 2009; Giannotti et al., 2019, 2016; Keenan et al., 1999; Khalil et al., 2016; Le Bocq et al., 2016; Nonnekes et al., 2019).

En effet, cet enregistrement de la marche consiste à réaliser un enregistrement vidéo, cinématique et cinétique avec le matériel respectif suivant : caméras numériques, système opto-électronique, plateforme de forces. Pour cet enregistrement, le patient est équipé de marqueurs réfléchissants et d'électrodes électromyographiques. Les marqueurs réfléchissants sont positionnés sur les points anatomiques définis par un modèle biomécanique. Ils servent à mesurer les mouvements segmentaires et articulaires en trois dimensions (cinématique). Il n'y a pas d'indicateurs consensuels pour l'analyse de l'AQM et cela nécessite une équipe d'ingénieurs et de médecins formés à l'interprétation de ces données. Il existe par ailleurs un délai entre l'acquisition et l'analyse définitive des données. Enfin ces analyses ne peuvent se dérouler que dans des locaux dédiés souvent à distance des lieux où le patient est suivi. Pour ces différentes raisons, l'AQM est difficile à mettre en place en pratique clinique courante par un praticien, notamment dans le cadre du suivi post opératoire des patients. Actuellement, les tests simples réalisables en consultation pour évaluer l'équilibre dynamique consistent principalement en l'observation du patient durant la marche et la quantification de la marche sur des pistes équipées. Ces pistes fournissent des indications précises sur la locomotion. Cependant, elles demandent un espace important pour les déployer, ne fournissent que des mesures directes au niveau des pieds et sont coûteuses (entre 10 et 20 k€). Il paraît donc exclu de les envisager en pratique médicale courante.

Nous avons réalisé un état des lieux des types d'évaluations post opératoires utilisées dans la littérature à la fois fonctionnelles et instrumentales. Aucune revue de la littérature antérieure n'a réalisé ce travail en se concentrant aux patients victimes d'AVC (Renzenbrink et al., 2012).

1.3.2 Revue de la littérature

Il existe une grande variété de pratique concernant l'évaluation de la marche chez le patient hémiparétique après AVC ayant un PVES. La revue de la littérature présentée ici fait un état des lieux complet des moyens utilisés pour évaluer la marche des patients de façon clinique ou instrumentale.



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EDITED BY

Maurizio Ferrarin,
Fondazione Don Carlo Gnocchi Onlus
(IRCCS), Italy

REVIEWED BY

Stefano Carda,
Centre Hospitalier Universitaire
Vaudois (CHUV), Switzerland
Paolo Zerbinati,
Ospedale Privato Accreditato Sol et
Salus, Italy

*CORRESPONDENCE

Nicolas de l'Escalopier
ndeescalopier@gmail.com

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Evaluation methods to assess the efficacy of equinovarus foot surgery on the gait of post-stroke hemiplegic patients: A literature review

Nicolas de l'Escalopier^{1,2*}, Cyril Voisard^{1,3}, Mona Michaud^{1,4},
Albane Moreau^{1,3}, Sylvain Jung^{5,6,7}, Brian Tervil⁵,
Nicolas Vayatis⁵, Laurent Oudre⁵ and Damien Ricard^{1,3,8}

¹Université Paris Cité, Université Paris Saclay, ENS Paris Saclay, CNRS, SSA, INSERM, Centre Borelli, Paris, France, ²Service de Chirurgie Orthopédique, Traumatologie et Réparatrice des Membres, Service de Santé des Armées, HIA Percy, Clamart, France, ³Service de Neurologie, Service de Santé des Armées, HIA Percy, Clamart, France, ⁴SYSNAV, Vernon, France, ⁵Université Paris Saclay, Université Paris Cité, ENS Paris Saclay, CNRS, SSA, INSERM, Centre Borelli, Gif-sur-Yvette, France, ⁶Université Sorbonne Paris Nord, L2TI, UR 3043, Villetaneuse, France, ⁷ENGIE Lab CRIGEN, Stains, France, ⁸Ecole du Val-de-Grâce, Service de Santé des Armées, Paris, France

Introduction: The aim of this study was to realize a systematic review of the different ways, both clinical and instrumental, used to evaluate the effects of the surgical correction of an equinovarus foot (EVF) deformity in post-stroke patients.

Methods: A systematic search of full-length articles published from 1965 to June 2021 was performed in PubMed, Embase, CINAHL, Cochrane, and CIRRIE. The identified studies were analyzed to determine and to evaluate the outcomes, the clinical criteria, and the ways used to analyze the impact of surgery on gait pattern, instrumental, or not.

Results: A total of 33 studies were included. The lack of methodological quality of the studies and their heterogeneity did not allow for a valid meta-analysis. In all, 17 of the 33 studies involved exclusively stroke patients. Ten of the 33 studies (30%) evaluated only neurotomies, one study (3%) evaluated only tendon lengthening procedures, 19 studies (58%) evaluated tendon transfer procedures, and only two studies (6%) evaluated the combination of tendon and neurological procedures. Instrumental gait analysis was performed in only 11 studies (33%), and only six studies (18%) combined it with clinical and functional analyses. Clinical results show that surgical procedures are safe and effective. A wide variety of different scales have been used, most of which have already been validated in other indications.

Discussion: Neuro-orthopedic surgery for post-stroke EVF is becoming better defined. However, the method of outcome assessment is not yet well established. The complexity in the evaluation of the gait of patients with EVF, and therefore the analysis of the effectiveness of the surgical management performed, requires the integration of a patient-centered functional dimension, and a reliable and reproducible quantified gait analysis, which is routinely usable clinically if possible.

KEYWORDS

equinovarus foot, hemiplegia, stroke, neuro-orthopedic surgery, gait analysis, IMU

Introduction

The number of hemiplegic stroke survivors is constantly increasing (1). They classically develop spastic equinovarus foot (EVF), posing a challenge for rehabilitation (2, 3). The position in plantar flexion and inversion results from an imbalance in hindfoot forces due to muscular hypertonia associated with loss of effective motor control. The development of EVF is associated with muscle over-activity of the calf muscles, triceps surae, tibialis posterior, flexor hallucis longus, flexor digitorum longus (FDL), and brevis muscles, combined with paresis or weakness of the antagonist muscles, the tibialis anterior (TA), peroneus longus, and brevis. Over time, flexible deformities typically evolve into fixed deformities as a result of muscle shortening consequent to prolonged contracture (4). This raises serious problems with footwear, upright stance, transfer, and gait. For severe deformities, non-operative treatment is usually unsatisfactory; neuro-orthopedic surgery is recognized as effective in improving foot position in spastic EVF (5, 6), usually achieving improvement in functional scores [most notably the Goal Attainment Scale (GAS)] (7–11). Triceps spasticity, ankle range of motion, and gait velocity are improved. In addition, the need for walking aids is reduced (2, 6, 12–15). There are many surgical techniques, which act on the tendons, in order to lengthen them, to transfer them or both. The most frequently performed intervention is split anterior tibialis tendon transfer (SPLATT) (16). Most of the time we lengthen the triceps surae through the Achilles tendon lengthening (TL) or through the gastrocnemius and soleus aponeurotomy to treat equinus position (17). Other tendon transfers are the extensor hallucis longus transfer (18), anterior transfer of the FDL (19), split posterior tibial transfer (20), and peroneus brevis transfer (21). Another type of surgical procedure aims to act directly on the nerves to reduce the spasticity of certain muscles. These are called selective neurotomies (SN). In EVF, most of the time, they concern the branches of the tibial nerve and, by reducing its caliber, make it possible to reduce spasticity (22–24). More rarely, bony procedures (BPs) are necessary. The details of these different techniques and the current management strategy have been described in a more generic literature review on EVF of all etiologies (16), as well as following the DELPHI method (25). The choice of the techniques used and their possible combination is based on the clinical examination of the patient through a multidisciplinary approach (15, 16). If non-operative techniques are insufficient, neuro-orthopedic surgery can correct the equinus, reduce spasticity, and provide plantigrade support. However, it is essential to accurately analyze the gait disorder in a dynamic manner to propose a program adapted to the patient without risking aggravating his condition. The evaluation of the outcome of the surgery must also be based on a quantified and objective method of analysis and not only on a subjective clinical impression.

Today, there is no standard, validated method for assessing gait improvement after post-stroke EVF surgery. Postoperative outcomes are heterogeneously assessed by quality of life scales, functional methods, such as the GAS, and by data from clinical examination, including splinting or barefoot walking. Change in gait pattern is difficult to analyze objectively and quantitatively, especially in longitudinal follow-up of patients. Quantified gait analysis techniques are effective but difficult to implement in routine clinical practice (26, 27). EVF is often evaluated by mixing different etiologies (TBI and cerebral palsy), and it seems important to us to evaluate a homogeneous patient population, here post-stroke EVF (28). The aim of this study was to realize a systematic review of the different ways, especially instrumental, used to evaluate the effects of surgical correction of post-stroke EVF deformities, including SN, tendon lengthening (TL), tendon transfer (possibly associated with TL), or BP, in post-stroke patients.

Methods

In this review, we defined a stroke as “an acute neurological dysfunction of vascular origin with sudden (within seconds) or at least rapid (within hours) occurrence of symptoms and signs corresponding to the involvement of focal areas of the brain” (29). Details of the protocol for this systematic review were registered on PROSPERO and can be accessed at https://www.crd.york.ac.uk/prospero/display_record.php?ID=CRD42022300497.

Search strategy and selection criteria

The literature search and analysis followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) (30) and Meta-analysis of Observational Studies in Epidemiology (MOOSE) (31). We searched the MEDLINE (via PubMed), Cochrane Central, and Embase electronic databases to identify articles published before 1 June 2021 that measured the efficacy of neuro-orthopedic surgery on the gait of hemiplegic post-stroke hemiplegic patients. In addition, the gray literature was searched in Google Scholar, [Opengrey.eu](https://www.opengrey.eu), [Greylit.org](https://www.greylit.org), WorldCat, World Health Organization Clinical Trials Search Portal, [ClinicalTrials.gov](https://www.clinicaltrials.gov), and the European Union Clinical Trials Register. All reference lists and bibliographies of included studies were also reviewed for relevant articles. The following MeSH headings and keywords were used: “equinus, equinovarus, foot deformity, foot deformities, hemiplegia, hemiparesis, stroke, cerebrovascular disorders, orthopedics, neuro-orthopedic, neurorehabilitation, surgery, and gait analysis”.

Selection criteria

As case series are probably the most frequent type of surgical report in the literature (32), it was decided not to restrict the selection to a specific study design. As a consequence, studies were included if they used either within-group pre-post treatment comparisons or between-group comparisons in a (at best randomized) controlled design. In addition, studies were required to meet the following inclusion criteria:

- investigating stroke in adults (irrespective of the phase of recovery);
- investigating the efficacy of surgical correction of EVF deformity (lengthening, release and/or transferring of muscles and/or tendons, and neurotomy);
- being written as a full-length article in the English, German, French, or Dutch language and being published in a peer-reviewed journal. If two or more articles were published by the same group, and if (within these articles) the etiology of the EVF deformity was comparable, only the study with the highest number of patients was included.

Methodological quality assessment and data extraction

The Oxford CEBM levels of evidence were used to grade the selected studies (33). The methodological index for non-randomized studies (MINORS) was applied to further assess the quality of each study (34). Few validated instruments are available to assess the methodological quality of observational or non-randomized studies. MINORS is a validated list designed to assess the methodological quality of non-randomized (surgical) studies (either comparative or non-comparative) comprising 12 items, the last four items of which apply only to comparative studies. Items are scored as 0 (not reported), 1 (reported but inadequate), or 2 (reported and adequate). The maximum score is 16 for non-comparative studies and 24 for comparative studies. Because no (randomized) controlled trials were identified, no pooling of data was possible, neither in a meta-analysis nor in a best-evidence synthesis. We collected all the modes of evaluation of walking that were used, including the instrumental analysis of gait, the clinical analysis, the scores and scales used, and the subjective feelings of the patients. The GAS (35–37) was also reported if it was used.

Results

Study selection

Figure 1 shows the study selection process as a flowchart. The initial systematic search strategy in PubMed identified

492 relevant citations (available on request). The search in the other databases did not yield additional articles. On the basis of the title, 301 studies were excluded for the following reasons: non-surgical studies; botulinum toxin evaluation; pediatric populations; other pathologies, such as cerebral palsy or Traumatic Brain Injury (TBI); other neurological foot deformities; or non-neurological deformity. Another 116 studies were excluded based on their abstracts. Recurrent reasons for exclusion were the use of interventions that did not fit within our definition, such as reduction by external fixator or successive cast, and the use of patient populations with an etiology other than stroke. The full texts of the remaining 75 studies were examined. Screening the references of these studies revealed eight additional articles. From these 83 initially selected studies, 50 studies were excluded in the second instance.

Methodological quality

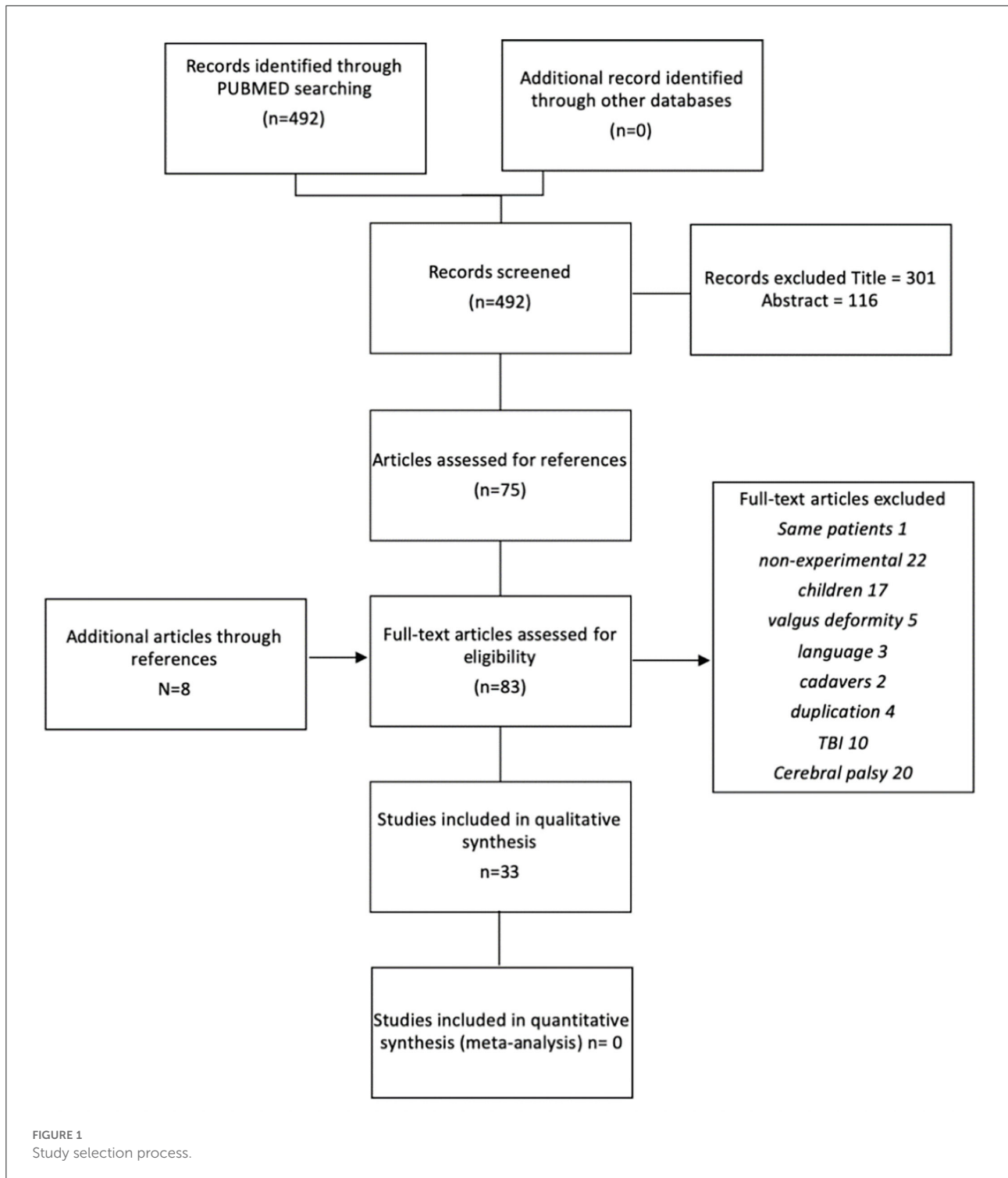
The characteristics of the different articles included in the study are summarized in Table 1. The methodological quality of the studies and their heterogeneity did not allow for a valid meta-analysis. The median score was 11/16, which is low. Only 17 of 33 studies involved exclusively stroke patients.

Surgical intervention

In view of the multitude of possible procedures, we preferred to classify the type of procedures performed into the following four categories: selective neurotomy (SN), tendon lengthening (TL), tendon transfer (possibly associated with TL), or bone procedure (BP). The studies and their associated categories are reported in Table 1. Ten studies (30%) evaluated only SNs, one study (3%) evaluated only TL procedures, 19 studies (58%) evaluated tendon transfer procedures, and only two studies (6%) evaluated the combination of tendon and neurological procedures, of which one evaluated only TL and one both TT and TL. Only one study (3%) evaluated exclusively BP procedures.

Clinical assessment

The criteria used in the clinical evaluation of patients are reported in Table 2. There are a wide variety of scales, most of which have been validated in other indications, such as cerebral palsy (e.g., the Physicians Rating Scale) (65). Some seem relevant but are rarely used, such as the FPI-6 (72). Only three studies performed a GAS, one of which did not meet the Turner-Stokes criteria (11). The measurement of passive range of motion (ROM) was the most recurring criterion found,



although its relevance for gait improvement was not assessed. On the contrary, the position of the foot during the oscillation phase, which is an essential element, was considered in only eight studies. Only 14 studies assessed patient satisfaction, mostly with

simple numerical scales. Patient reported outcome measures were widely used, and only SF-36 (6) or SATISPART Stroke (39). GAS was used only one time (6), and a kind of unvalidated GAS one time (52).

TABLE 1 Characteristics of the different studies included.

Authors	Study design	Minors	Number of subjects	Age	Time since injury	Type of intervention	Follow-up (months)
Boffeli et al. (38)	Cases series, uncontrolled, prospective, single center, non-blinded	12	12 strokes	61 (54–73)	108 (11–240)	TL	29 (12–63)
Bollens et al. (39)	RCT, assessor blinded	20	8 strokes	50 (32–70)	30 (8–84)	SN	6
Buffenoir et al. (40)	Cases series, uncontrolled, prospective, multi center, non-blinded	12	34 strokes/55 patients	43.5 (12–54)	64 (3–320)	SN	10 (4–24)
Buffenoir et al. (41)	Historically controlled, prospective, monocenter, non-blinded	8	4 strokes/7 patients	41 (19–71)	37 (10–45)	SN	1
Buffenoir et al. (42)	Cases series, uncontrolled, prospective, mono center, non-blinded	11	9 strokes/15 patients	47 (22–66)	86 (12–84)	SN	15
Carda et al. (43)	Cases series, uncontrolled, retrospective, single center, non-blinded	13	177 strokes	50 (SD 14)	67	TT, TL	12
Decq et al. (44)	Cases series, uncontrolled, prospective, mono center, non-blinded	12	18 strokes/46 patients	36 (8–79)	96	SN	15 (8–28)
Delattre et al. (45)	Cases series, uncontrolled, retrospective, single center, non-blinded	6	9 strokes/10 patients	56 (30–80)	NC	TT, TL	51.7 (18–132)
Deltombe et al. (23, 46)	Cases series, uncontrolled, prospective, mono center, non-blinded	11	30 strokes	45 (20–69)	48 (15–218)	SN	24
Deltombe et al. (6)	Cases series, uncontrolled, prospective, mono center, non-blinded	12	18 strokes	55.7 ± 10.2	NC	SN, TT, TL	12
Edwards and Hsu (17)	Cases series, uncontrolled, retrospective, single center, non-blinded	9	9 strokes/11 patients	55 (23–72)	34	TT, TL	39 (12–79)
Gasse et al. (47)	Cases series, uncontrolled, retrospective, single center, non-blinded	6	14 strokes/22 patients	39.9 (17–76)	NC	TT, TL	6
Giannotti et al. (48)	Cases series, uncontrolled, retrospective, single center, non-blinded	8	47 strokes	56 ± 15	72 ± 60	TT, TL	1
Giannotti et al. (49)	Cases series, uncontrolled, prospective, mono center, non-blinded	11	24 strokes	55 (29–74)	60 (±36)	TT, TL	12
Keenan et al. (50)	Historically controlled, prospective, single- center, non-blinded	14	22 strokes /33 patients	40 (18–62)	NC	TT, TL	41 (17–53)
Khalil et al. (51)	Cases series, uncontrolled, retrospective, single-center, non-blinded	8	6 strokes/16 patients	38 ± 15.2	112 ± 90	SN, TL	10.7 ± 6.8

(Continued)

TABLE 1 (Continued)

Authors	Study design	Minors	Number of subjects	Age	Time since injury	Type of intervention	Follow-up (months)
Le Bocq et al. (52)	Cases controlled, prospective, single-center, non-blinded	11	23 strokes	57 (48–63)	28 (15–37)	SN	5
Lemos and Pereira (53)	Cases series, uncontrolled, retrospective, single-center, non-blinded	5	21 strokes/27 patients	49 (18–72)	7.1 (2–22)	TT, TL	29 (12–84)
Mazzoli et al. (54)	Cases series, uncontrolled, prospective, single-center, blinded	13	24 strokes	55 (29–74)	60 (36)	TT, TL	12
Mooney and Goodman (55)	Cases series, uncontrolled, retrospective, single-center, non-blinded	4	194 strokes	55 (17–84)	NC	TT, TL	6
Morita et al. (56)	Historically controlled, retrospective, single-center, non-blinded	11	125 strokes	57 (32–78)	23 (6–132)	TT, TL	33 (24–74)
Namdari et al. (57)	Cases series, uncontrolled, retrospective, single-center, non-blinded	12	64 strokes	54 (24–74)	65.7 (17–523)	TT, TL	12 (3–42)
Nonnekes et al. (58)	Cases series, uncontrolled, retrospective, single-center, non-blinded	6	10 strokes	48 (30–62)	84 (12–288)	BP, TL	7 (2–11)
Ono et al. (59)	Cases series, uncontrolled, retrospective, single-center, non-blinded	8	32 strokes /39 patients	(18–76)	>12	TT, TL	6
Pinzur et al. (26)	Cases controlled, prospective, single-center, non-blinded	13	36 strokes/54 patients	57 (17–77)	38 (12–204)	TT, TL	30 (24–62)
Reddy et al. (60)	Cases series, uncontrolled, retrospective, single-center, non-blinded	12	26 strokes	55 (23–72)	75	TT, TL	18 (6–48)
Rousseaux et al. (61)	Historically controlled, prospective, monocenter, non-blinded	14	34 strokes	50 (11–45)	45 (7–293)	SN	12
Rousseaux et al. (24)	Cases series, uncontrolled, prospective, monocenter, non-blinded	12	51 strokes	51 ±12	44 (11–304)	SN	24
Sindou and Mertens (62)	Cases series, uncontrolled, retrospective, single-center, non-blinded	9	19 strokes/53 patients	36 (6–68)	48 (2–17)	SN	36 (12–120)
Tracy (12)	Cases series, uncontrolled, retrospective, single-center, non-blinded	6	22 strokes/35 patients	40 (18–62)	36	TT, TL	32 (4–76)
Vogt (63)	Cases series, uncontrolled, retrospective, single-center, non-blinded	12	42 strokes/69 patients	47 (8–79)	50	TT, TL	44 (12–168)
Vogt et al. (64)	Cases series, uncontrolled, retrospective, single-center, non-blinded	6	80 strokes/132 (82 patients studied)	47 (11–78)	79 (13–486)	TT, TL	Mean 65

(Continued)

TABLE 1 (Continued)

Authors	Study design	Minors	Number of subjects	Age	Time since injury	Type of intervention	Follow-up (months)
Yamamoto et al. (13)	Cases series, uncontrolled, retrospective, single-center, non-blinded	9	75 strokes	57	18	TT, TL	77

Type of intervention: SN, selective neurotomy; TL, tendon lengthening; TT, tendon transfer (possibly associated with TL) or BP, bone procedure.

Gait assessment

Instrumental gait analysis refers to all modes of gait analysis using objective and quantified parameters. The types of instrumental analyses that were performed in the included studies are presented in Table 2. Quantitative gait analysis (QGA) is the gold standard for the study of human gait using reflectors attached to the body. It consists of video (kinematic and kinetic recording using digital cameras), an optoelectronic system, and a force platform. BP refers to a simple baropodometric and COP displacement study, and some studies performed only an elementary analysis including speed and number of steps. BP refers to a simple baropodometric and COP displacement study, and some studies performed only an elementary analysis including speed and number of steps.

Eleven studies conducted a non-instrumental walking analysis. Six studies used the 10-Meter Walk Test (10MWT), and one study used the 6-Minute Walk Test (6MWT). Note that the 6MWT did not show any correlation with the functional scores achieved in this study (54). In one study, only the walking velocity was evaluated over 10 m (56). Four studies used sensorless video recording, allowing for secondary measurement of analytical joint mobility by several observers (6, 23, 44, 45). Instrumental gait analysis was performed in only 10 studies (26, 39, 41, 43, 48–52, 58) (Table 3), and only six studies associated it with clinical and functional analyses (Table 2). It was only performed pre-operatively in one study and postoperatively in one study. In two studies, it was not performed on all the patients who were operated on. Regarding spatiotemporal parameters, the most frequently used were elementary parameters that did not require any specific indicators, such as speed or step length.

Three studies evaluated symmetry by various means. Le Bocq et al. (52) used non-paretic step length divided by paretic step length as defined by Patterson et al. (73); for Nonnekes et al. (26), step length asymmetry was quantified by using a step length ratio defined as the difference in step length between the paretic and non-paretic sides divided by the average step length of the paretic and non-paretic sides (positive values indicate a larger paretic step compared to the non-paretic step). For Giannotti et al. (48, 49), gait stability and symmetry were represented by anterior step length and double support time but without any analysis. The authors did not recover the raw data (51, 58), and data analysis was performed by

engineers or software, so the method used to obtain the results was not explicit and therefore not reproducible. Kinematics analysis evaluated ankle ROM and sometimes knee ROM. Ankle dynamic ROM was the most frequently used criterion. The only criteria used in the analysis were closed-chain joint kinematics and spatiotemporal parameters. No scores or other assessment methods were used. To the best of our knowledge, inertial measurement systems, largely used in other context of walk assessment in other conditions (74), have never been studied in this type of study.

Outcomes

Functional results according to the main criterion used by the studies, as well as complications, and follow-up in months are summarized in Table 4. None of the studies had unfavorable results, and the complication rate was quite low. However, the wide variety of procedures and the differences in the collection of complications or residual deformities did not yield global conclusions. The response to the primary endpoint of the studies is reported in the right-hand column. There was no homogeneity in the evaluation criteria.

Discussion

To the best of our knowledge, our review is the only one dealing exclusively with the management of EVF in adult hemiplegic post-stroke patients, focusing on evaluation methods of the impact of the surgery on gait. Indeed, in our opinion, to better specify the management and the consequence of possible surgical procedure in the gait pattern, it is necessary to study cohorts of patients with the same pathology. Some studies mixed patients with amyotrophic lateral sclerosis, multiple sclerosis, Little's disease, TBI, and stroke (42, 44). Moreover, it is the first review to include both the classical clinical analysis and the instrumental analysis of walking, which should become essential in the years to come. It highlights not only the lack of consensus on the clinical criteria used in the evaluation of gait but also the poor access to quantified analysis in routine clinical practice. The main limit of this review lies in the fact that no meta-analysis was possible because of the statistical weaknesses of the included

TABLE 2 Clinical exams and type of gait analysis realized.

Authors	Instrumental assessment of preoperative gait	Instrumental assessment of postoperative gait	Non-instrumental gait analysis	Clinical exam	Foot position stance	Foot position swing	Walking speed	Spatiotemporal parameters	Orthotic use	Walking capacity	Patient satisfaction	Gas	Others
Boffeli et al. (38)	No	No	No	British foot score, Yes MMST, ankle ROM	No	No	No	No	Yes	No	No	No	
Bollens et al. (39)	QGA	QGA	10MWT	Tardieu, MAS, MRC, PROM	No	No	Yes	Yes	No	No	SATISPART-stroke	No	SIAS
Buffenoir et al. (40)	No	No	10MWT	Equinus foot score, PROM, stretch reflex scale	No	No	Yes	Yes	Yes	Yes	No	No	
Buffenoir et al. (41)	Video-EMG gait analysis	Video-EMG gait analysis	No	General examination, PROM, tardieu, analytic exam	Yes	No	Yes	Yes	Yes	No	Patient satisfaction score/10	No	
Buffenoir et al. (42)	No	No	No	Ashworth, stretch reflex, equinus foot score, PROM	Yes	No	No	No	Yes	Yes physicians rating scale (37), independent walking score	Yes	No	Electrophysiological and biomechanical with specified devices
Carda et al. (43)	QGA	QGA	Spatiotemporal parameters	Walking handicap score	No	No	Yes	Yes	No	No	No	No	
Decq et al. (44)	No	No	Kinematic gait assessment on video, individual qualitative assessment	Ashworth, tardieu, PROM	Yes	Yes	No	No	Yes	No	No	No	
Delattre et al. (45)	No	No	Video record of gait	FPI-6 (65)	Yes	No	No	No	No	No	Yes	Yes	
Deltombe et al. (23, 46)	No	No	10MWT, video record of gait	Ashworth, MRC, PROM	Yes	Yes	Yes	Yes	No	No	No	No	

(Continued)

TABLE 2 (Continued)

Authors	Instrumental assessment of preoperative gait	Instrumental assessment of postoperative gait	Non-instrumental gait analysis	Clinical exam	Foot position stance	Foot position swing	Walking speed	Spatiotemporal parameters	Orthotic use	Walking capacity	Patient satisfaction	Gas	Others
Deltombe et al. (6)	No	No	10MWT, video record of gait	Modified Ashworth Scale (63), Tardieu, MRC, PROM/AROM	Yes	No	Yes	Yes	Yes	Yes, FWC (66), ABILOCO (67)	Yes	Yes	SIAS, SF-36
Edwards and Hsu (17)	No	No	No	Kling et al. classification (68)	No	No	No	No	No	No	No	No	No
Gasse et al. (47)	No	No	No	No	No	No	No	No	No	No	Yes, %	No	No
Giannotti et al. (48)	QGA	QGA	No	No	Yes	Yes	Yes	Yes	No	No	No	No	No
Giannotti et al. (49)	QGA	QGA	No	No	No	No	Yes	Yes	No	No	No	No	No
Keenan et al. (50)	QGA	QGA but only 20 patients	Yes, descriptive	Ambulatory scale	Yes	Yes	No	No	Yes	No	No	No	Dynamic EMG
Khalil et al. (51)	COP	COP	No	No	No	No	No	No	No	No	No	No	No
Le Bocq et al. (52)	QGA	QGA	No	MAS, MRC, PROM, LL-FAS, NFAC (69)	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	(-4.4)
Lemos and Pereira (53)	No	No	No	Perception of improvement on gait	No	No	No	No	Yes	Yes	Yes	No	Questionnaire non-valid
Mazzoli et al. (54)	No	No	6MWT	NPRS, CGI-C, FAC, RMI, WHS	No	No	Yes	Yes	Yes	Yes	No	No	No
Mooney and Goodman (55)	No	No	No	Quantitative assessment of walk	Yes	No	No	No	No	Yes	No	No	No
Morita et al. (56)	No	QGA 25/125	No	Walking ability	Yes	No	No	No	Yes	Yes, walking ability	No	No	No

(Continued)

TABLE 2 (Continued)

Authors	Instrumental assessment of preoperative gait	Instrumental assessment of postoperative gait	Non-instrumental gait analysis	Clinical exam	Foot position stance	Foot position swing	Walking speed	Spatiotemporal parameters	Orthotic use	Walking capacity	Patient satisfaction	Gas	Others
Namdari et al. (57)	Yes	No	No	Viosca score (qualitative assessment of gait)	Yes	Yes	Yes	Yes	Yes	Viosca (70)	No	No	
Nonnekes et al. (58)	QGA	QGA	No	FAC	No	No	Yes	Yes	No	FAC, 1-10	No	No	
Ono et al. (59)	No	No	No	Qualitative gait analysis	Yes	No	No	No	No	No	Yes	No	
Pinzur et al. (26)	QGA	QGA	No	PROM	Yes	Yes	No	Yes	Yes	Non	Yes	No	
Reddy et al. (60)	QGA	No	No	Qualitative gait analysis	No	No	No	No	Yes	Viosca (70)	No	No	
Rousseaux et al. (61)	No	No	10MWT	MAS, MRC, FAC, No RMA (71)	No	No	Yes	Yes	Yes	FAC	Yes, 0-3	No	
Rousseaux et al. (24)	No	No	Gait pattern, 10MWT	MAS, PROM, ICF, MRC, RMA, FAC	Yes	No	Yes	Yes	Yes	FAC	Yes, 0-3	No	
Sindou and Mertens (62)	No	No	No	Ashworth, PROM, AROM, MRC	Yes	No	No	No	Yes	No	No	No	
Tracy (12)	No	No	No	Qualitative gait analysis	Yes	Yes	No	No	Yes	Yes	No	No	
Vogt (63)	No	No	No	Descriptive clinical exam	Yes	No	No	No	Yes	Yes, ability to walk 1-5	Yes	No	
Vogt et al. (64)	No	No	No	Qualitative gait analysis focused on knee flexion	Yes	Yes	No	No	Yes	Yes, functional autonomy 1-5	No	No	
Yamamoto et al. (13)	No	No	No	Qualitative gait analysis	No	No	Yes	No	Yes	Yes	Yes	No	

MMST, Manual muscle strength testing; A-P/ROM, Active/Passive range of motion; MAS, Motor assessment scale; MRC, Medical research council; SIAS, Social interaction anxiety scale; FPI-6, Foot posture index; 10MWT, 10 meter walk test; 6MWT, 6 minute walk test; FWC, Functional walking categories; QGA, Quantitative gait analysis; EMG, Electromyogram; LL-FAS, Lower limb function assessment scale; NFAC, New functional ambulation classification; RMI, Rivermead mobility index; NPRS, Numeric pain rating scale; CGI-C, Clinical global impression of change; WHS, Walking handicap score; RMA, Rivermead motor assessment.

TABLE 3 Characteristics and methodology of instrumental gait analysis performed to assess postoperative hemiplegic gait.

Study	Protocol	St Parameters	Kinematic	Kinetic
Bollens et al. (39)	Three-dimensional analysis (38, 40). Segmental kinematics were recorded by eight infrared cameras (200 Hz) with the Eliclinic system (BTS, Milan, Italy), while the patients were walking at a comfortable speed on a treadmill (Mercury LTMed, HPCosmos, Nussdorf, Germany). The ground reaction forces (GRFs) were synchronously recorded (200 Hz) using four strain gauges located under the corners of the treadmill (Pharos System Inc, Rochester, NY), and the net joint movements in the sagittal plane were computed from the GRF, kinematic, and anthropometric data.	–	Ankle and knee ROM	–
Buffenoir et al. (41)	Video analysis with self-adhesive markers that were placed on the lateral surface of the spastic limb at fixed points. These markers were used to measure the range of knee and ankle flexion during computerized analysis of the video recording.	10MWT	Ankle and knee ROM	–
Carda et al. (43)	S.A.F.Lo. protocol (17, 46). Nine 15 mm reflective markers (lower prominence of the sacrum, posterior superior iliac spines, lateral femoral condyles, lateral malleoli, and fifth metatarsal heads). ELITE [ELaborazione Immagini Televisive] three-dimensional system (BTS SpA, Milan, Italy) with polyelectromyography and two piezo-electric force platforms (Kistler AG, Winterthur, Switzerland). All patients were assessed while barefoot.	Self-selected speed, swing velocity, cadence, step length, stride length, and step Body speed of advancement during healthy swing phase (mean linear velocity of the marker placed on the sacrum during the swing phase of the unaffected limb. The measure is representative of body progression over the paretic foot).	Maximum ankle dorsiflexion	Center of pressure (COP) posterior-anterior progression (47, 55) COP posterior-anterior regression COP posterior-anterior crossover Posterior-anterior GRF positive and negative peak Vertical GRF Ankle power absorption and generation peak during stance phase
Giannotti et al. (48, 49)	Six camera motion capture system, (sMart-dX, BTS Bioengineering, Milan, Italy) and two force platforms (Kistler aG, Winterthur, Switzerland) with markers placed according to the conventional protocol (57)	Gait symmetry and stability: anterior step length and double support time Balance: step width Walking ability: speed, cadence, and stride length	Ankle DF at initial contact, maximum DF at stance and maximum DF at swing	–

(Continued)

TABLE 3 (Continued)

Study	Protocol	St Parameters	Kinematic	Kinetic
Keenan et al. (50)	Bidirectional slow-motion video recording with GRF	Walking velocity Cadence Stride time	-	-
Le Bocq et al. (52)	Two-dimensional video recording system. The spatiotemporal gait parameters were evaluated using an 8-meter GAITRite® mat (CIR Systems Inc., Sparta, NJ, USA). Two trials (each over a total distance of 10 m [i.e., starting about a meter before the mat and finishing about a meter afterwards]) were performed at a comfortable speed and then averaged. These two objective gait measurements were performed barefoot and assistive.	Gait speed and cadence Non-paretic and paretic step lengths Gait asymmetry (as defined by Patterson et al.: non-paretic step length/paretic step length) (73): Paretic swing Total stance Single support phase durations (as a percentage of the gait cycle)	Gait Assessment and Intervention Tool (GAIT) (59) Ankle and knee ROM	-
Nonnekes et al. (58)	Reflective markers were placed at anatomical landmarks according to the full-body Plug-in-Gait model (61). Marker positions were recorded by an eight camera 3D motion analysis system (Vicon Motion Systems, United Kingdom) at a sample rate of 100 Hz. GRFs under both feet were recorded at a sample rate of 1000 Hz by two force plates (AMTI Custom 6 axis composite force platform, USA). Kinetics and kinematics were calculated with Vicon Clinical Manager software. Kinematic	Walking speed Cadence Stride length, step length and single- support time of both the paretic and nonparetic leg. Step length asymmetry was quantified by using a step length ratio defined as the difference in step length between the paretic and nonparetic side divided by the average step length of the paretic and nonparetic side (positive values indicate a larger paretic step compared to the nonparetic step).	Ankle ROM	Internal peak ankle moment Peak ankle power of the paretic and nonparetic leg.
Pinzur et al. (26)	Preoperative dynamic EMG and electrogoniometry	Double support phase length Stance phase length	-	-
Khalil et al. (51)	Data were collected using the F-Scan in-shoe system. It allows people to walk in normal shoes, using an insole measuring device to detect changes in COP displacements or plantar pressures . The recording frequency is 50 Hz, and the data are recorded and processed in the system's software (F-Scan Mobile Research 5.72 software).	-	-	Anteroposterior displacement of the COP measured from the most anterior to the most posterior points Lateral deviation of the COP measured from the two most lateral points Posterior Margin of foot contact measured from the most posterior point of heel contact to the most posterior point of the COP trajectory

TABLE 4 Primary endpoint results of the different studies.

Authors	Strokes/ subjects	Complications	Residual or recurrent deformities	Follow-up (months)	Main criterion
Boffeli et al. (38)	12	0	25%	29 (12–63)	BFS 55–35, $p = 0.0022$
Bollens et al. (39)	8	3	NC	6	Ankle stiffness L-path significantly decreased from T0 (482.95 ± 163.20 N m rad ⁻¹) to T1 (172.17 ± 102.88 N m rad ⁻¹)
Buffenoir et al. (40)	34/55	9%	0	10 (4–24)	Equinus foot score decreased from 1.54 preoperative to 0.273 after neurotomy (t test; $p < 0.0001$)
Buffenoir et al. (41)	4/7	0	0	1	Mean patient satisfaction score 7.7/10
Buffenoir et al. (42)	9/15	0	1	15	90% improvement of clinical spasticity scores, 20% improvement of walking scores
Carda et al. (43)	177	8	3	12	WHS 3.78 (SD 1.31) to 5.13 (SD 1.04) $p < 10^{-3}$
Decq et al. (44)	18/46	0	0	15 (8–28)	100% improvement of equinus deformity
Delattre et al. (45)	9/10	0	3	51.7 (18–132)	–5.9 to –3.5 FPI-6
Deltombe et al. (23, 46)	25/30	0	0	24	Significant decrease in triceps surae spasticity, an increase in gait speed, and a reduction in equinus and varus in swing and stance phases at 2 months postoperatively.
Deltombe et al. (6)	18	8	0	12	GAS score [median (quartile 1–quartile 3)] observed at T1 [52.3 (46.6–59.1)] and T2 [52.3 (46.6–66.0)] $p < 0.05$
Edwards and Hsu (17)	9 / 11	1	3	39 (12–79)	King et al. three Good, four Excellent, two Poor
Gasse et al. (47)	14 / 22	2	2	6	90% contracts fulfilled; 100% were satisfied (41%) or very satisfied (59%) with their operation
Giannotti et al. (48)	47	0	0	1	Ankle df increased 1 month after surgery at all investigated gait phases (Wilcoxon test, $p < 0.0001$)
Giannotti et al. (49)	24	0	0	12	Variables relating to ankle kinematics improved toward their normal values at 1 month after surgery.
Keenan (50)	22/33	0	0	41 (17–53)	100% correction of deformity; improvement of ambulatory status.
Khalil et al. (51)	6/16	NC	NC	10.7 ± 6.8	COP variation for the paretic limb, a significant increase of AP was observed after block (13.5 vs. 12.3 cm, $p = 0.02$) and after surgery (13.7 vs. 12.3 cm, $p = 0.03$). A significant decrease of PM was observed after surgery (4.5 vs. 3.3 cm, $p < 0.001$) with no more difference between two limbs (2.8 vs. 3.3 cm, $p = 0.44$).
Le Bocq et al. (52)	23	3	2	5	TNN had a very marked effect on the level of spasticity and the range of motion in dorsiflexion ($p < 10^{-3}$).
Lemos and Pereira (53)	27	11	0	29 (12–84)	Patients experienced frank improvement in terms of gait, orthostatic posture, self-esteem and quality of life.
Mazzoli et al. (54)	24	0	0	12	All variables but the 6MWT were significantly improved (Wilcoxon test, $p < 0.05$) at T1 or T2 and this remained until the 12-month mark.
Mooney et al. (55)	194	9	6	6	Improvement of subjective walking capacity
Morita et al. (56)	125	1	46	33 (24–74)	91/125 able to walk without a brace

(Continued)

TABLE 4 (Continued)

Authors	Strokes/ subjects	Complications	Residual or recurrent deformities	Follow-up (months)	Main criterion
Namdari et al. (57)	64	NC	NC	12 (3–42)	All patients were corrected to a plantigrade foot at final follow-up examination; 49 of 64 patients (76.6%) had an improved ambulatory status postoperatively as measured by Viosca score
Nonnekes et al. (58)	10	0	NC	7 (2–11)	Walking speed significantly improved by 32% after surgery (0.38 ± 0.20 m/s to 0.50 ± 0.17 m/s, $p = 0.007$).
Ono et al. (59)	39	No data	Toe curling	6	In all cases, correction of the equinovarus deformity was achieved and maintained.
Pinzur et al. (26)	36/54	2	2	30 (24–62)	Equinus deformity was corrected in all patients and 59% of them were brace-free.
Reddy et al. (60)	26	0	NC	18 (6–48)	Reduction in the use of nonoperative therapies in caring for patients with this condition.
Rousseaux et al. (61)	34	13	0	12	TNN (M3, M6 and Y1) resulted in a more significant effect than BTI (D15, M2 and M5) on most of the measures: ankle plantar flexor spasticity, range of movement in dorsiflexion and eversion, foot position in upright situation, functional ambulation categories (barefoot), RMA, gait velocity (comfortable condition), subjective benefit and use of walking aids.
Rousseaux et al. (24)	51	10	0	24	Neurotomy definitely reduced spasticity and improved motor control on antagonist muscles while improving balance, walk, and the RMA.
Sindou and Mertens (62)	19/53	6	11	36(12–120)	Complete suppression of disabling spasticity
Tracy (12)	22/13	1	6	32 (4–76)	91% removal orthosis
Vogt (63)	42/69	12	11	44 (12–168)	Significant improvement in patient autonomy ($p < 0.001$), demonstrated by an improved ability to ambulate independently and a decreased need to wear orthopedic shoes ($p < 0.001$) and orthoses ($p < 0.001$), as well as an increased ability to wear normal shoes ($p < 0.001$).
Vogt et al. (64)	80/132 (82 studied)	6	8	Mean 65	80/82 patients were able to walk barefoot, 74 reported an increase in their walking distance, and 73 could regularly wear normal shoes.
Yamamoto et al. (13)	75	NC	14	77	Correction was maintained in 74% of patients; 79% did not use an orthosis; 51% could bathe unassisted; and 76% were satisfied with the results.

BFS, Bristol Foot Score; WHS, Walking Handicap Score; FPI-6, Foot Posture Index; GAS, Goal Attainment Scale; COP, Center of Pressure; TNN, Tibial Nerve Neurotomy; 6MWT, 6 Minute Walk Test; RMA, Rivermead Motor Assessment.

studies. This has already been noticed in previous reviews on the subject (28).

Surgical strategy

There is great heterogeneity of attitudes, divided between neurological and tendinous procedures, due to the fact that

they are performed by different surgical teams. For several years, the performance of all these procedures by the same teams has made it possible to refine the indications and to perform combined procedures (6, 15, 16, 25). Few series have analyzed the results of this global management. It is important that future series do not take into account only one procedure or another, but the “neuro-orthopedic” management itself.

Clinical assessment

Numerous scales and measurement methods have been used, but none of them has imposed itself. This clearly shows the absence of a validated generic scale for evaluating walking in hemiplegics. On the contrary, the measurement of joint kinematics in analysis, although easily achievable and reproducible, does not give a good idea of what really happens in the closed chain during walking. Moreover, the type and importance of the global deficit are variable, and the resulting functional discomfort is specific to each patient. For this reason, it is extremely difficult to obtain a functional scale that can be adapted to each situation. Some have simply used a scale of satisfaction and the feelings of the patients with different subjective criteria (53).

The GAS is a method for quantifying progress on personal goals. Turner-Stokes's guide to the GAS is a method for quantifying progress toward personal goals (11). Turner-Stokes's guide and the use of Kiresuk's T-score (75) are the most widely used GAS-based approaches in rehabilitation (37). This personalized analysis allows to directly evaluate the success of the intervention, according to the defined objective. It represents a sensitive and specific analysis of the result. Indeed, in other pathologies, the GAS and the overall clinical impression have shown a significant correlation (7, 9). Moreover, in rehabilitation, the GAS is more sensitive to change than the Barthel Index and the Functional Independence Measure (8–10). In some studies, the GAS was the only scale capable of detecting change after treatment (8, 76). Standard scales sometimes show no change, while the GAS goal is achieved. The main reason for this is that the goals and fixed GAS often do not correspond to any of the items in the standard scales (77). For us, this functional analysis must now be part of the systematic clinical analysis of the outcome of the intervention. The limitation of this method lies in the definition of pre-operative goals, since it must be sufficiently ambitious but still achievable. Regarding the evaluation of spasticity, as explained by Deltombe et al. (22), although the Ashworth scale is commonly used in the literature, it is confounded by contracture, as increased resistance to movement is not only exclusively dependent on stretch reflex activity but also due to increased stiffness as a result of contracture. The Tardieu scale seems more appropriate, especially to evaluate triceps spasticity (78). Reddy et al. (60) used the evaluation of the reduction of non-operative care associated with an EVF deformity, which seems to be a relevant criterion (60).

Gait assessment

Traditional non-instrumental scales have moderate effectiveness. The 6MWT does not appear to be a relevant indicator. As used in the study by Mazzoli et al. (54), it shows no

difference pre- and postoperatively, while all functional scores are improved. Its use is, therefore, not relevant in this indication. The 10MWT provides some information, notably on step length and speed. However, this analysis does not detail the intrinsic quality of walking. As we said before, there is no correlation between the analysis of the open and closed chain gaits, and if the analytical analysis is easily done and traceable in the medical record, global analysis of gait is more difficult to assess in an objective way. In some retrospective studies, data concerning the exact position of the foot during the gait cycle were too unequally reproduced in patient files to be properly exploited (64). This pre- and postoperative comparison of the gait analysis seems essential to evaluate the effect of the procedure. For example, the comparison of pre- and postoperative joint kinematics is a reliable and reproducible criterion that can be measured by instrumental analysis (43). For this purpose, instrumental gait analysis methods are of considerable help. The gold standard is QGA, which provides more precise data for assessing surgical outcome, to improve the surgical program in spastic EVF and define more standardized strategies (27). While QGA represents the gold standard, the availability of facilities and immediacy of results makes QGA challenging to use in routine clinical. Indeed, there is no consensus on QGA indices, as such a consensus requires a team of engineers and physicians trained in interpreting such data. There is also a delay between acquisition and final analysis. Finally, the analysis can only be conducted in dedicated premises, often located far from where the patient lives or is being followed. For all these reasons, QGA is difficult for doctors to implement in routine clinical practice and postoperative follow-up. Presently, there are some simple tests for assessing dynamic balance in consultation, basically consisting of observing the patient walking and quantifying gait on an equipped walkway. However, we saw that instrumental gait analyses were scarce and of widely varying quality to evaluate EVF treatment in post-stroke adults. In addition, no validated and reproducible indicators were used. For example, only three studies evaluated pitch symmetry, and the three indicators were different. Most studies used instrumental analysis only to collect simple spatiotemporal data or joint kinematics data, which represents a limited contribution. No team collected the raw signal data for analysis, and they used the parameters provided by the brand's software but not their own algorithm. Moreover, the raw data were not accessible in open source. Moreover, QGA provides precise data on locomotion, but they require large and specific spaces, are very expensive (between €10,000 and €40,000), and hardly suited for everyday medical practice. Recently, a study by Mazzoli et al. (54) showed a good correlation between indices based on ground reaction force and clinical and functional variables. Since the acquisition of ground reaction forces does not require patient preparation, it can be used in clinical routine and especially for postoperative evaluation (79). An alternative is to use combined accelerometric and gyroscopic data on an inertial measurement

unit (IMU). IMUs have the advantage of being lightweight, inexpensive, and easy to use in practice. It has been validated for clinical use in gait assessment in patients with osteoarthritis or neurological pathology, such as post-stroke hemiplegia (74, 80–83). Another advantage is the possibility to perform ambulatory measurements over a longer period of time in the patient's environment (84), which is not feasible with QGA. On the contrary, the comparison with the norms of healthy subjects is a criterion that is not often used but seems to be correlated with walking improvement. This cross-sectional step study represents a complementary element in the evaluation of postoperative improvement (26).

Conclusion

Neuro-orthopedic surgery for post-stroke EVF is becoming better defined. However, outcome assessments are not yet well established. The complexity of the evaluation of gait of patients with EVF, and therefore the analysis of the effectiveness of the surgical management performed, requires the integration of a patient-centered functional dimension, as well as a reliable and reproducible quantified gait analysis, and if possible usable in routine clinical practice. Therefore, it seems necessary, in future, to compare the results of a systematic instrumental analysis with the functional results.

Data availability statement

The original contributions presented in the study are included in the article/supplementary

material, further inquiries can be directed to the corresponding author.

Author contributions

NI'E: writing and submission of the article. MM, CV, SJ, and BT: writing and correction. AM, NV, LO, and DR: conception and correction. All authors contributed to the article and approved the submitted version.

Conflict of interest

Author MM was employed by company SYSNAV. Author SJ was employed by company ENGIE.

The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Cette revue de la littérature met évidence le fait qu'il n'existe pas de méthode objective, reproductible et facilement utilisable en routine clinique dans l'analyse post opératoire du pied varus équin spastique. La grande variété d'échelles fonctionnelles différentes et le faible recours à l'analyse instrumentale de la marche compliquent l'évaluation de l'impact sur la marche des patients opérés des différentes interventions. D'autre part les centrales de mesures inertielle, qui ont montré un intérêt pour suivre la marche chez des patients atteints de pathologies neurologiques ou ostéo-articulaires (Vienne et al., 2017) n'ont jamais été utilisées dans cette indication..

1.3.3 Apport de l'Inertialolocographie

L'Inertialolocographie (ILG) est une solution alternative pour étudier le contrôle locomoteur des patients qui s'appuie sur des mesures conjointes accélérométriques et gyroscopiques par des centrales de mesure inertielle ou Inertial Measurement Unit (IMU). Ces IMUs sont des capteurs autonomes d'utilisation très facile puisqu'ils ne nécessitent pas de locaux dédiés, en effet ils mesurent l'accélération du capteur, la vitesse angulaire et calculent son orientation à l'aide d'une combinaison d'accéléromètres, de gyroscopes et de magnétomètres. Ils sont mis en place directement sur le patient à l'aide de bande velcro. Le recueil des données peut se faire sur un ordinateur ou une tablette de façon immédiate ce qui permet leur usage en consultation ou dans un service médical hospitalier. Une importante littérature existe sur l'utilisation de l'ILG dans la caractérisation de la marche (rapport Haute Autorité de Santé de 2007). L'ILG a déjà été utilisée pour l'analyse comportementale fine (réalisation du demi-tour) de la marche et du risque de chute chez des patients hemiparétiques par Barrois et al. en 2017 (Barrois et al., 2017) ainsi que, plus récemment, dans l'évaluation du pied tombant après AVC par Feuvrier et al. (Feuvrier et al., 2019). Plus généralement, la quantification de la marche par ILG a montré son efficacité dans différentes populations comme les personnes souffrant d'arthrose, les patients cérébro-lésés ou atteints de pathologies neurologiques comme la Sclérose en Plaque (SEP) (Barrois et al., 2016, 2015; Mizuike et al., 2009; Vienne et al., 2017; Yang et al., 2013). Concrètement, des centrales inertielle qui mesurent la vitesse angulaire

en 3D à l'aide d'un gyroscope tri axial (Oudre et al., 2018), l'accélération selon trois axes, le champ magnétique terrestre selon trois axes de n'importe quel segment mobile du corps sont disposées à différents points (en nombre limité, 3 points suffisent) sur le patient. Les centrales inertielles utilisées par le centre Borelli (Xsens Awinda) sont alimentées par des batteries dont la longévité est 3,5 heures si le capteur est actif. Les acquisitions se font à une fréquence d'échantillonnage de 100 Hz. Les capteurs permettent de mesurer des accélérations jusqu'à 16 g et des vitesses angulaires jusqu'à 1200 deg/s. Les incertitudes sont respectivement 0,003 m/s² et 0,05 deg/s. La taille des capteurs est 3,5 x 5,8 x 1,0 cm³. Ils pèsent 27 g. Les accéléromètres communiquent avec ordinateur par ondes radio aux alentours de 22 MHz. Leur coût est raisonnable, de l'ordre de 1000 euros /capteur, logiciel compris. Le signal obtenu par les deux IMUs situés sur les pieds est utilisé pour segmenter les différentes phases de la marche. Ensuite les données obtenues par le capteur situé sur le tronc et celles des pieds vont permettre de déterminer les données cinématiques et temporelles utilisées pour mesurer un nombre très important d'indicateurs d'intérêt utilisant des paramètres mathématiques validés dans la littérature (Vienne et al., 2017). La chaîne de mesure utilisée est simple et validée. Une analyse de la marche sur 10 mètres aller et retour avec demi-tour utilisant les unités de mesure inertielles permet d'obtenir un bilan immédiat de la marche (Dot et al., 2020).

La problématique principale est d'obtenir, à partir du signal brut, des indicateurs utiles au clinicien, et au patient, un retour visuel facilement analysable permettant notamment une comparaison aux mesures antérieures dans le suivi longitudinal des patients. Pour cela, de nombreux indicateurs ont été publiés ces dernières années. Si l'utilisation d'un seul indicateur paraît séduisante car facilement quantifiable et compréhensible, elle n'en demeure pas moins limitée dans l'analyse de la marche globale (Gulde et al., 2021). D'autre part les indicateurs préférentiels ne sont pas les mêmes en fonction des pathologies (Melendez-Calderon et al., 2021). Pour une approche la plus globale possible, mais permettant une analyse aisée, il nous a paru important de sélectionner les indicateurs quantitatifs uniques compilant l'ensemble des paramètres d'intérêt selon la pratique de cliniciens expérimentés et de les représenter en un objet unique. Afin d'apporter l'ensemble des résultats de façon immédiate, l'utilisation d'un diagramme en radar telle qu'elle a déjà été utilisée pour représenter les caractéristiques biomécaniques de la marche semble être l'approche la plus adaptée

(Angelini et al., 2021; Mansour et al., 2017). La mesure de l'évolution relative de l'aire de ce diagramme constitue une grandeur unique d'intérêt dans l'évaluation de la sensibilité de notre outil.

1.4 Contexte de travail : le centre Borelli et l'HIA Percy

Le Centre Borelli¹ (Figure 3) est issu de la fusion de deux unités CNRS, le CMLA (Centre de Mathématiques et de Leurs Applications) créé à l'ENS de Cachan au début des années 1990 et Cognac G (Cognition and Action Group) initié en 2014 à l'Université Paris-Descartes. Le Centre Borelli est une unité mixte de recherche (UMR 9010) réunissant des chercheurs en mathématiques, en informatique et en neurosciences et des médecins très investis dans les interfaces avec le domaine biomédical et le transfert industriel. Il est implanté sur plusieurs sites dont l'ENS Paris-Saclay, l'Université Paris Cité (Campus Saint-Germain-des-Prés), et les hôpitaux d'Instruction des Armées Bégin et Percy. La spécificité du Centre Borelli est de développer des connaissances fondamentales en neurosciences et en mathématiques, des méthodes scientifiques dans la modélisation, la simulation et le traitement de données complexes, des démarches cliniques et des outils logiciels. Le format particulier du Centre Borelli permet une interaction forte entre les cliniciens, les ingénieurs et les mathématiciens. Les échanges y sont permanents et permettent d'utiliser des outils techniques innovants dans des applications très pratiques et centrées sur la clinique. Le développement de l'analyse de la marche par centrales de mesures inertielles a été initié il y a plus de 8 ans (Barrois et al., 2015, 2017; Dot et al., 2020; Oudre et al., 2018; Truong et al., 2019). Une antenne du centre Borelli est située à Percy ce qui permet une unité de lieu indispensable favorisant les échanges entre cliniciens et chercheurs et l'acquisition de données patients et ainsi de transformer en objet de recherche les données issues de l'activité clinique de routine (Figure 4).

¹ <https://centreborelli.ens-paris-saclay.fr/>



Figure 3 : Le Centre Borelli

Concernant la pathologie étudiée, les équipes de chirurgie orthopédique et de MPR de l'HIA Percy sont spécialisées dans la prise en charge des séquelles de l'appareil locomoteur d'origine traumatique ou neurologique. Depuis plusieurs années, en partenariat avec l'Institution Nationale des Invalides et le Centre de Rééducation Fonctionnelle des 3 soleils, une Unité de Neuro-Orthopédie et de Chirurgie du Handicap s'est spécialisée plus spécifiquement dans la prise en charge des atteintes musculo squelettiques des atteintes neurologiques centrales parmi lesquelles les séquelles d'AVC, les traumatismes crâniens et les blessures médullaires².

Nous avons la conviction que l'association de ces deux équipes expertes et passionnées dans leur domaine permettra de poursuivre et d'intensifier la collaboration entre chercheurs et cliniciens afin d'améliorer la prise en charge des patients cérébrolésés.

² <https://www.hiapercy.sante.defense.gouv.fr/services/unite-de-neuro-orthopedie-et-de-chirurgie-du-handicap/>



Figure 4 : Exemple d'analyse de la marche avec le protocole décrit utilisant des centrales de mesures inertielles Xsens® sur les pieds, le tronc et la tête réalisée lors d'une consultation de routine à l'hôpital Percy.

1.5 Objectifs

1.5.1 Objectif principal

L'objectif principal de notre travail est l'identification d'indicateurs pertinents en clinique, la mise au point de leur obtention automatique à partir de signaux bruts d'ILG, et la constitution d'un indicateur unique quantitatif résumant l'évolution de ces indicateurs pour le suivi longitudinal prospectif d'une cohorte de patients opérés d'un PVES suite à un AVC. Notre critère de jugement principal sera l'évaluation de la sensibilité et la spécificité de l'évolution de l'aire globale du diagramme en radar des indicateurs retenus, avant et après la chirurgie de PVES des patients par rapport à l'évolution de l'échelle fonctionnelle GAS.

2. Matériel et méthodes

2.1 Schéma de l'étude

Il s'agit d'une étude prospective, monocentrique, longitudinale, non randomisée.

- Une cohorte d'apprentissage de patients SEP été incluse en consultation de Neurologie à l'hôpital Percy entre juin 2018 et septembre 2018 afin de mettre en place l'automatisation de la détermination des indicateurs pertinents à partir de l'ILG.
- Une cohorte de normalisation constituée de sujets sains a été recrutée parmi le personnel de l'hôpital et de l'unité de recherche clinique entre juin 2018 et septembre 2018.

Pour ces deux cohortes les participants ont été suivis pendant 12 mois.

- Une cohorte de patients atteints de PVES ouverte de septembre 2019 à décembre 2021 à l'HIA Percy-Clamart, service de chirurgie orthopédique et service de neurophysiologie pour l'objectif principal de notre travail. Les patients hémiplegiques souffrant d'un PVES après un AVC, pris en charge à l'HIA Percy sur cette période par un seul chirurgien (Nicolas de l'Escalopier) étaient inclus. Pour la cohorte PVES, la durée de suivi des patients était de 6 mois avec 3 mesures : une mesure pré opératoire (V0), une mesure après 3 mois (évolution de court terme), une mesure après 6 mois (évolution finale).

Cette étude a reçu l'approbation du Comité Protection des Personnes Nord-Ouest III (ID RCB: 2017-A01538-45). Tous les participants ont reçu une fiche d'informations et ont donné leur consentement éclairé par écrit avant d'être inclus (Annexe 1).

2.2 Critères d'éligibilité

2.2.1 Sujets sains

Les critères d'inclusion pour la cohorte de sujets sains étaient :

- Absence de chutes au cours des 5 dernières années avant l'inclusion (les chutes ont été définies comme des événements qui conduisent la personne debout ou marchant

sur le sol de manière non intentionnelle, sans être poussée ou tirée de l'extérieur, indépendamment du fait qu'une blessure soit subie ou non (Zecevic et al., 2006)).

- L'absence de maladie pouvant affecter la marche et le fait d'être considéré en bonne santé après un examen clinique effectué par des médecins parmi les enquêteurs.

2.2.2 Patients atteints de SEP

Les participants atteints de SEP ont été recrutés en consultation de Neurologie à l'hôpital Percy entre juin 2018 et septembre 2018.

Les critères d'inclusion de la cohorte SEP étaient :

- Patient âgé de plus de 18 ans
- Patient avec un diagnostic de SEP selon les critères du panel international de 2010 (Polman et al., 2011)
- Patient mobile, pouvant marcher 4 séries de 20m avec demi-tour, avec une pause de 3 min entre chaque exercice avec ou sans aide technique
- Patient n'ayant pas d'autre affection affectant la marche

Le seul critère d'exclusion était la grossesse.

2.2.3 Patients atteints de PVES

Les patients de la cohorte PVES étaient recrutés par le biais de consultation pluri disciplinaire de neuro-orthopédie. Ces consultations réunissent l'ensemble des spécialistes prenant en charge les séquelles neurologiques de l'appareil locomoteur, à savoir des Médecins de médecine physique et réadaptation (MPR), des chirurgiens orthopédiques, des neurologues, des kinésithérapeutes. L'indication chirurgicale était donc envisagée par une équipe spécialisée après une prise en charge médicale optimale. Les patients étaient opérés à l'HIA Percy par le Docteur de l'Escalopier, qui était présent à l'ensemble des consultations.

Les critères d'inclusion étaient :

- Patient âgé de plus de 18 ans ;
- Patient ayant donné son consentement éclairé ;
- Patient affilié à un régime de sécurité sociale ;

- Patient ayant un pied varus équin spastique nécessitant pour lequel la consultation de neuro-orthopédie a retenu l'indication d'un traitement chirurgical ;
- Patient mobile, pouvant marcher 4 séries de 20m avec demi-tour, avec une pause de 3 min entre chaque exercice avec ou sans aide technique
- Patient en mesure de comprendre les consignes du CSCT.

Les critères de non-inclusion :

- Patient âgé de moins de 18 ans ;
- Refus du patient ;
- Patient non affilié à un régime de sécurité sociale ;
- Patient non marchant
- Antécédent d'intervention chirurgicale sur la cheville ou le pied à opérer.
- Antécédent modifiant la marche du patient de façon majeure.
- Patient dans l'incapacité de comprendre les consignes du CSCT.

2.3 Déroulement de l'étude

Schéma récapitulatif du suivi du patient atteint de PVES (Figure 5)

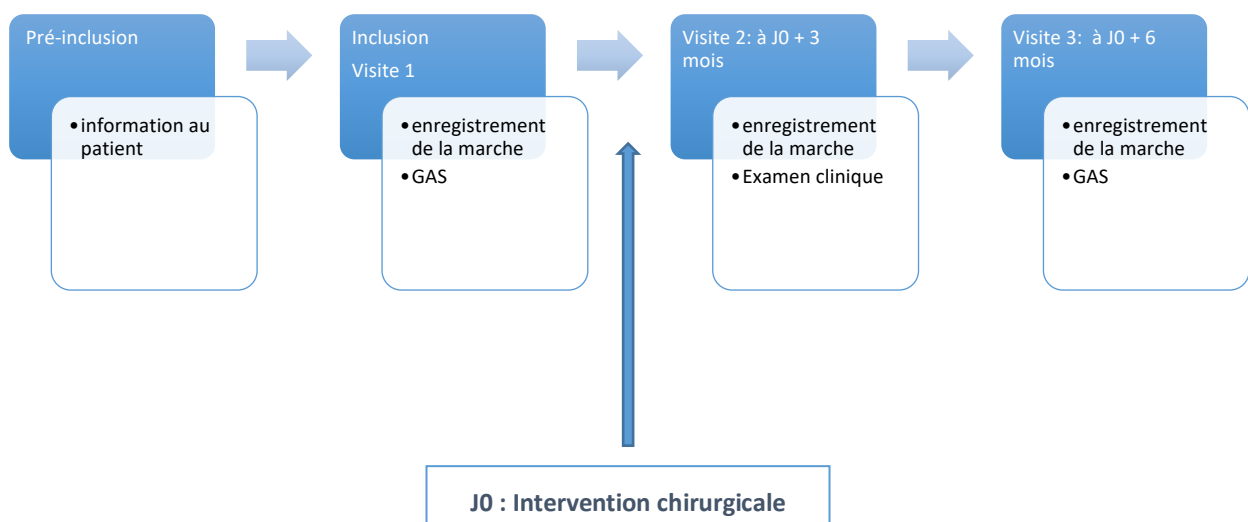


Figure 5 : Flow chart des visites du patient inclus dans l'étude

Phase de pré-inclusion : Les sujets sont vus en consultation pluri disciplinaire de neuro orthopédie afin de valider collégalement la stratégie chirurgicale et de l'intégrer au mieux à leur prise en charge en rééducation. Si le patient réunissait les critères d'inclusion, le médecin investigateur proposait au sujet de participer à la recherche. Il l'informait de l'objectif, de la nature des contraintes, des bénéfices attendus de la recherche, du traitement informatisé des données le concernant au cours de cette recherche et lui précisait également ses droits d'accès, d'opposition et de rectification à ces données. Il répondait également à toutes ses questions. Un document d'information et un formulaire de consentement résumant ces différents points était remis au sujet. Après cette information, le sujet disposait d'un délai de réflexion d'au moins 48h.

Phase d'inclusion : le sujet donnait au médecin investigateur son accord éclairé pour participer à l'étude. Un exemplaire de la note d'information et du consentement signé est alors remis au sujet. L'exemplaire original est conservé par le médecin investigateur dans un lieu sûr inaccessible à des tiers.

2.4 Protocole d'enregistrement de la marche

Nous utilisons 4 IMUs pour mesurer les accélérations linéaires et les vitesses angulaires. Ces 4 capteurs (XSens® MTw Measurement Units, fréquence d'échantillonnage de 100 Hz) étaient placés sur le dos de chacun des deux pieds, au niveau du pelvis (vertèbres L4-L5), et sur le front (Figure 6) avec des bandes adhésives (Velcro) ajustables fournies par le fabricant.



Figure 6 : Centrale de mesure inertielle Xsens® Awinda utilisée. Fixations sur les deux pieds et le bassin à l'aide de bandes velcro.

Après la fixation des capteurs, le patient exécutait la séquence suivante : maintien de la position debout à l'arrêt pendant 6s, marche sur 10m à vitesse confortable, demi-tour, marche sur 10m à vitesse confortable, arrêt et maintien de la position debout pendant 2s (Figure 7). Un enregistrement de la marche se faisait ensuite sur 6 mètres par le GAITRite® (Figure 8), un tapis analysant le déroulé du pas, les données recueillies étaient synchronisées afin d'améliorer la détection des pas. Les patients exécutaient la séquence chaussés puis pieds nus sans aide technique si cela était possible ou avec leur aide technique habituelle. Un ordinateur recueillait les enregistrements des capteurs Xsens® et du tapis GAITRite®.

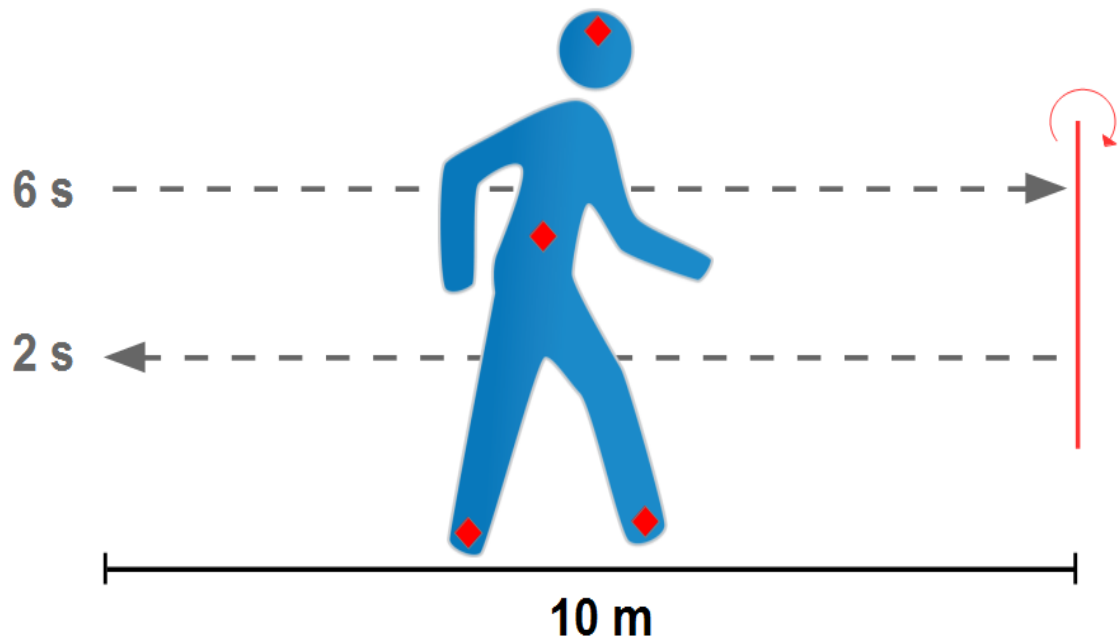


Figure 7 : Schéma explicatif du protocole utilisé avec demi-tour libre.



Figure 8 : Illustration d'un passage sur tapis GAITRite® de 6mètres permettant d'avoir une segmentation des pas automatisée sans demi-tour.

2.5 Recueil de données cliniques

2.5.1 Patients atteints de SEP

Pour la **cohorte de patient SEP**, le score EDSS était évalué par le clinicien suivant le patient de façon habituelle.

2.5.2 Cohorte PVES

L'évaluation fonctionnelle du résultat du transfert était réalisée à l'aide de la GAS afin de disposer d'une évaluation concernant la réussite fonctionnelle de l'intervention d'après le contrat pré opératoire posé entre l'équipe et le patient. A l'aide d'une fiche validée le patient exprimait ses attentes et leurs importances respectives dans son handicap en pré-opératoire. En post opératoire le patient et l'équipe évaluaient le résultat. Si celui-ci était atteint comme prévu le score était de 0. Si le résultat était meilleur que celui attendu le score était de +1 ou + 2 en fonction de l'importance de l'amélioration. S'il n'y avait pas d'amélioration fonctionnelle le score est de -1 et si le patient est aggravé -2. 3 ou 4 objectifs peuvent être évalués par la GAS. Puis le score est calculé afin d'obtenir un T score sur 50.

Un **Examen clinique** classique était par ailleurs réalisé par l'investigateur, afin de mesurer la mobilité de la cheville, le bon fonctionnement du transfert, ainsi qu'un testing analytique du pied.

2.6 Analyse des données

Une fois le recrutement des patients, la réalisation des interventions chirurgicales respectant les recueils des données cliniques et accélérométriques selon le protocole, l'analyse des données était le suivant :

2.6.1 Détection automatisée du pas

La première étape d'analyse du signal a nécessité le développement et la validation d'un algorithme de détection automatisée des événements de la marche, étape indispensable pour rendre notre outil utilisable en routine clinique, sans nécessiter de segmentation manuelle ou l'utilisation d'un tapis GAITRite®. Ces résultats sont présentés dans la partie 3.1.

2.6.2 Semiogramme

Le développement d'un outil visuel d'analyse de la marche appelé semiogramme a ensuite été validé sur une cohorte de patients ayant déjà été enregistrés auparavant. Cela a permis de juger de la reproductibilité et de l'intérêt du semiogramme sur le suivi d'une pathologie chronique avec atteinte de la marche. Afin d'obtenir une représentation unique compilant les paramètres d'intérêt de la littérature, nous avons listé l'ensemble des paramètres mathématiques utilisés dans l'analyse de la marche à partir d'une revue de la littérature récente (Vienne et al., 2017) que nous avons mis à jour afin de rechercher d'éventuels paramètres plus récents (Beck et al., 2018; do Vale Garcia et al., 2021; Figueiredo et al., 2020; Iijima et al., 2019; Melendez-Calderon et al., 2021; Pinto et al., 2019). Nous avons voulu utiliser cet outil, en le rendant directement utilisable par le clinicien, ne nécessitant pas de connaissance ou d'intermédiaire.

Afin de le rendre pertinent, nous avons réuni un comité d'experts présents dans l'équipe investigatrice et impliqués dans l'analyse de la marche. Les participants étaient issus de différentes spécialités : neurologie, chirurgie orthopédique, MPR. Nous avons identifié huit critères cliniques que sont la vitesse moyenne et les sept dimensions capitales d'analyses de la marche :

- Fluidité (Smoothness) : fait référence à la continuité ou à l'absence d'intermittence de la marche (Balasubramanian et al., 2015)
- Vigueur (Sturdiness) : fait référence à l'amplitude du pas.
- Symétrie (Symmetry) : fait référence à la correspondance droite / gauche pendant la marche
- Stabilité (Stability) : fait référence à l'équilibre de la démarche
- Régularité (Steadiness) : correspond au caractère régulier de la marche
- Élasticité (Springiness) : fait référence au rythme de la marche

- Synchronisation (Synchronization) : correspond à la coordination entre les membres pendant la marche.

Nous avons ensuite sélectionné les meilleurs paramètres mathématiques pour chacun de ces critères cliniques (Vienne et al., 2017). La présentation finale est un diagramme en radar, qui a déjà été utilisé, pour des indicateurs biomécaniques et non cliniques, afin de permettre une analyse visuelle simplifiée et rapide de la marche (Angelini et al., 2021; Mansour et al., 2017). Le diagramme en radar obtenu devrait permettre une analyse immédiate quantitative de la marche permettant de visualiser la qualité globale de la marche par rapport à une cohorte de sujets sains, chaque dimension étant normée, mais aussi de réaliser un suivi longitudinal facile dans les pathologies chroniques. Ce diagramme en radar, qui a pour vocation d'ouvrir l'œil du clinicien à un nouveau champ sémiologique, est appelé semiogramme dans la suite de l'étude. L'utilisation préalable de données de suivi d'une cohorte d'apprentissage de patients atteints de SEP semble être le prérequis pour mettre au point et entraîner des algorithmes d'automatisation de calcul des indicateurs à partir du signal brut issu des IMUs portés par les patients ainsi que valider l'outil comparativement au score EDSS qui est utilisé dans le suivi longitudinal des patients SEP et permet une étude de corrélation. Ces résultats sont présentés dans la partie 3.2.

2.6.3 Cohorte PVES

La dernière partie de cette thèse a consisté à évaluer la faisabilité, la reproductibilité et l'intérêt de l'analyse de la marche par ILG utilisant le semiogramme dans l'évaluation post opératoire des patients opérés de PVES post AVC. Nous avons utilisé pour cela comme critère principal la variation de l'aire du semiogramme pondérée par la vitesse moyenne. Le calcul de l'aire étant sensible à l'échelle utilisée et à l'ordre des paramètres autour du diagramme, nous avons établi arbitrairement l'ordre mentionné précédemment pour une valeur de Z-score allant de 2 à -20 afin d'avoir une précision suffisante pour les marches très dégradées. La formule de la surface du semiogramme pondérée par la vitesse moyenne est la suivante :

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

Où :

- Z_{speed} représente le Z-score de la vitesse moyenne
- Pour i compris entre 1 et 7, Z_i représente le Z-score du $i^{\text{ème}}$ paramètre
- Z_8 représente le Z-score du premier paramètre ($Z_8 = Z_1$)

Nous avons ensuite étudié la variation de l'aire du semiogramme chez les patients ayant une amélioration fonctionnelle ($GAS \geq 0$) et chez les patients n'ayant pas d'amélioration ou une détérioration ($GAS < 0$), l'objectif étant d'évaluer la concordance entre l'augmentation de la courbe et l'amélioration fonctionnelle et inversement. Ces résultats sont présentés dans la partie 3.3.

3. Résultats

3.1 Segmentation automatisée des pas

L'étape clef pour analyser le signal brut des IMUs et calculer les indicateurs repose sur une segmentation fiable et automatisée des différentes étapes de la marche au niveau des pieds sur le sol. Si la segmentation du pas des sujets sains ne présente aujourd'hui pas de difficulté particulière (Caldas et al., 2017; Dot et al., 2020; Lim et al., 2022; Pacini Panebianco et al., 2018), lorsqu'il s'agit de patients souffrant de pathologie neurologique et ayant des marches très déstructurées le challenge reste important (Fasano and Mancini, 2020; Hendriks et al., 2022; Snijders et al., 2007). L'utilisation d'un dispositif lourd dont le plus simple est un tapis de marche GAITRite® permet une segmentation partielle du signal dans ces cas difficiles (Menz et al., 2004). Cependant ce dispositif alourdit la procédure, ne donne aucun élément sur la phase oscillante à distance du sol et ne permet pas une analyse du demi-tour, ou un examen d'un exercice de marche sur une longueur plus importante que celle du tapis. Afin de permettre une plus grande liberté dans la réalisation des enregistrements de marche, une segmentation automatique ne nécessitant pas d'instruments autres que les IMUs s'avère nécessaire. Pour mettre au point cette méthode, il faut disposer de deux éléments :

- L'obtention du signal brut, sans prétraitement ou modification réalisée par une interface commerciale vendue avec le produit.
- La conception d'un algorithme de détection du pas dont la fiabilité aura été éprouvée comparativement au gold standard que représente le GAITRite®.

Pour la réussite de notre travail destiné à une utilisation en pratique clinique courante, nous avons donc voulu développer un algorithme original utilisant des outils connus et validés, permettant une analyse de la marche rapide et reproductible à partir du signal issu d'IMUs, efficace sur les patients neurologiques. Ce travail est présenté dans l'article suivant.

Automatic Gait Events Detection with Inertial Measurement Units: Healthy Subjects and Moderate to Severe Impaired Patients

Cyril Voisard (✉ cyril.voisard@gmail.com)

University of Paris-Saclay

Nicolas De l'Escalopier

Université Paris-Cité

Damien Ricard

Hôpital d'instruction des Armées Percy

Laurent Oudre

University of Paris-Saclay

Research Article

Keywords: pathological gaits, gait analysis, step detection, pattern recognition, Intertial Measurement Units, Dynamic Time Warping

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Automatic Gait Events Detection with Inertial Measurement Units: Healthy Subjects and Moderate to Severe Impaired Patients

Cyril Voisard^{1,3*†}, Nicolas de l'Escalopier^{2,4†}, Damien Ricard^{2,3,5} and Laurent Oudre¹

Correspondence:

Yrilyl.voisard@etu.u-paris.fr
Université Paris Saclay, Université
Paris Cité, ENS Paris Saclay,
INSERM, SSA, INSERM, Centre
d'Évaluation des Technologies
de Santé, Gif-sur-Yvette, France
Full list of author information is
available at the end of the article
Equal contributor

Abstract

Background: Recently, the use of inertial measurement units (IMUs) in quantitative gait analysis has been widely developed in clinical practice. Numerous methods have been developed for the automatic detection of gait events (GEs). While many of them have achieved high levels of efficiency in healthy subjects, detecting GEs in highly degraded gait from moderate to severely impaired patients remains a challenge. In this paper, we aim to present a method for improving GE detection from IMU recordings in such cases.

Methods: We recorded 10-meter gait IMU signals from 13 healthy subjects, 29 patients with multiple sclerosis, and 21 patients with post-stroke equino varus foot. An instrumented mat was used as the gold standard. Our method detects GEs from filtered free acceleration and gyration signals. Firstly, we use autocorrelation and pattern detection techniques to identify a reference stride pattern. Next, we apply multiparametric Dynamic Time Warping to annotate this pattern from a model stride, in order to detect all GEs in the signal.

Results: We analyzed 16,819 GEs recorded from healthy subjects and achieved an F1-score of 100%, with a median absolute error of 8 ms (IQR [3-13] ms). In multiple sclerosis and equino varus foot cohorts, we analyzed 6067 and 8951 GEs, respectively, with F1-scores of 99.4% and 96.3%, and median absolute errors of 18 ms (IQR [8-39] ms) and 26 ms (IQR [12-50] ms).

Conclusions: Our results are consistent with the state of the art for healthy subjects and demonstrate a good accuracy in GEs detection for pathological patients. Therefore, our proposed method provides an efficient way to detect GEs from IMU signals, even in degraded gaits. However, it should be evaluated in each cohort before being used to ensure its reliability.

Keywords: pathological gaits; gait analysis; step detection; pattern recognition; Inertial Measurement Units; Dynamic Time Warping

Background

The study of gait in medicine is an essential tool for evaluating the health and progression of patients with various diseases [1]. In this context, quantitative gait analysis can be used to finely evaluate the patient's functional abilities, track the progression of their disease, measure the effectiveness of treatments, and develop personalized rehabilitation plans [2, 3].

In recent years, inertial measurement units (IMUs) have become widely developed in gait analysis due to their compact size, low cost, and ease of integration [4, 5]. They allow for objective and quantitative gait analysis, easy to use in healthy subjects, athletes [6] and patients, for example with neurological or orthopedic diseases [7]. They allow therefore the measurement of indicators on the gait semiology of patients, such as speed, stride length, double-support time, and balance [8]. Some of these features depend on the segmentation of strides and steps. Based on the historical description of gait in healthy subjects, 4 GE occur in a stride, in this order: Heel-Off (HO), Toe-Off (TO), Heel-Strike (HS), and Foot-Flat (FF) [9, 10]. Two main phases are described: the Stance Phase (StP) when the foot is on the ground between HS and TO, and the Swing Phase (SwP) when the foot is in the air between TO and HS [11, 12].

To accurately identify GEs from IMU signals, many techniques have therefore been developed. Currently, automatic detection of GEs on IMU recordings in healthy subjects has achieved a high degree of accuracy and continues to improve, with many efficient algorithmic techniques detecting GEs with a median absolute error of less than a tenth of a second [13, 14, 15]. However, the results on pathological subjects are often less precise, especially when gait is severely degraded. Due to the complexity of the sensory and motor commands that control gait, patients with advanced neurological pathologies can have particularly unstructured gaits [16, 17, 18]. For example, Ji *et al.* showed a 4 times lower accuracy in detecting the end of the step in hemiplegic subjects compared to healthy subjects [19]. Moreover, most of the algorithms tested on impaired patients have only been tested in a few specific diseases [20, 21, 22, 23]. Therefore, one of the current challenges is to improve GE detection in pathological gaits.

A recent literature review has referenced the most commonly used mathematical principles in the exercise of IMU-based gait analysis [24]. This study summarizes research practices regarding IMU positioning, algorithmic methods, and algorithm validation processes. Over the past few years, the 3 most commonly found types of methods have been the Hidden Markov Model (HMM) [25], the Wavelet Transform (WT) [9], inspired by the study of ECGs, and rule-based detections (RBD) utilizing various mathematical tools [13, 26]. The study recommends the use of RBD with IMUs placed on the ankle or foot, validated using pressure sensors as ground truth.

Recently, Deep Learning algorithms have also proven successful in detecting GEs [23].

Among the RBD algorithms, template-based methods have shown promising results in segmenting GEs in healthy subjects [27, 28, 10]. This technique relies on the creation of a reference dictionary of steps, which is used for segmentation of the signal by pattern recognition and extraction [29]. The use of a unique step dictionary allows for GE segmentation in healthy subjects [29, 10]. However, in neurological diseases, this method requires the addition of a solution for imprinting the patient's step, such as an instrumented mat [28], making the deployment in routine clinical practice impossible. Another area for improvement concerns the use of different pattern extraction methods, such as Dynamic Time Warping (DTW) [30, 10]. DTW is a technique that promises precise detection of signal variations and similarity, and has already been used in gait analysis [31, 27].

The objective of this study is to develop a reliable algorithm for detecting degraded gaits using only IMUs, making it suitable for routine clinical use. To achieve this, we propose a new method for detecting Gait Events (GEs) in degraded gaits using IMUs. Firstly, we estimate stride length using the autocorrelation method [32]. This enables us to identify a reference stride by comparing it to a pre-defined model stride for similarity using a targeted matrix profile algorithm [33]. Next, we use the jerk and gyration signals and apply a multiparametric Dynamic Time Warping (mDTW) algorithm to annotate the reference stride. Finally, we use correlation and mDTW to detect all GEs of the signal using the annotated stride as a template, following the same method as previously employed [10].

This new automatic GE detection algorithm is based on the raw acceleration and gyration data collected by the IMUs and requires neither manual annotation nor external tools. To evaluate its efficiency, we test it in comparison with an instrumented mat, considered the gold standard in gait segmentation [34], as well as with template-based state-of-the-art techniques [29, 10].

Methods

Cohorts

All the gait data were recorded at Percy Military Hospital (Clamart, France) from June 2018 to September 2021. 13 healthy control subjects (CS) who reported no

medical impairment and were considered healthy after a clinical examination by medical doctors among investigators, 29 patients with multiple sclerosis (MS), and 21 post-stroke hemiplegic patients with spastic equino varus foot (EVF) requiring surgical intervention were enrolled. Included participants had to be mobile and able to walk 4 sets of 20m with u-turn with a 3-minute break between each set, with or without medical assistance. Patients who were unable to walk, had a history of ankle or foot surgery, or had a history that could alter gait were excluded. Each subject in the CS cohort participated in 1 or 2 sessions, each consisting of 4 to 42 recordings. Patients in the MS cohort participated in 1 or 2 sessions with 4 to 6 recordings each, as described in [28]. Patients in the EVF cohort were recorded preoperatively and during follow-up visits at 3 and 6 months. All participants provided written informed consent before inclusion. The study protocol followed the principles of the Declaration of Helsinki and was approved by the ethics committee "Protection of Persons North West III" (RCB ID: 2017-A01538-45).

Data Acquisition

Equipment

Two sensors MTw Awinda XSens[®] (weight 16 g, dimensions 47 mm × 30 mm × 13 mm, sensitivity ± 2000 deg/s and ± 160 m/s², XSens[®] Technologies, Enschede, the Netherlands) (XS) were placed on the dorsal part of each foot of participants using Velcro bands. The sensor reference frame axes, which are used in subsequent analyses, are specified in Figure 1. A 6-meter GAITRite[®] walkway (GR) was placed in a wide corridor of the hospital. The acquisition frequencies for XS and GR were 100 Hz and 120 Hz, respectively. Both systems were time-synchronized with the Awinda Recording and Docking Station to within 10 μ s.

Figure 1 Presentation of the sensor. (A): Tw Awinda XSens[®] sensor; (B) Definition of the axis for the sensor on the left foot.

Experience

An experiment involves walking straight for 10 meters at a comfortable speed while wearing the foot sensors, with 6 meters of the walk on the GAITRite[®] walkway. Initialization and termination of the walk are performed outside the mat, and the

Figures

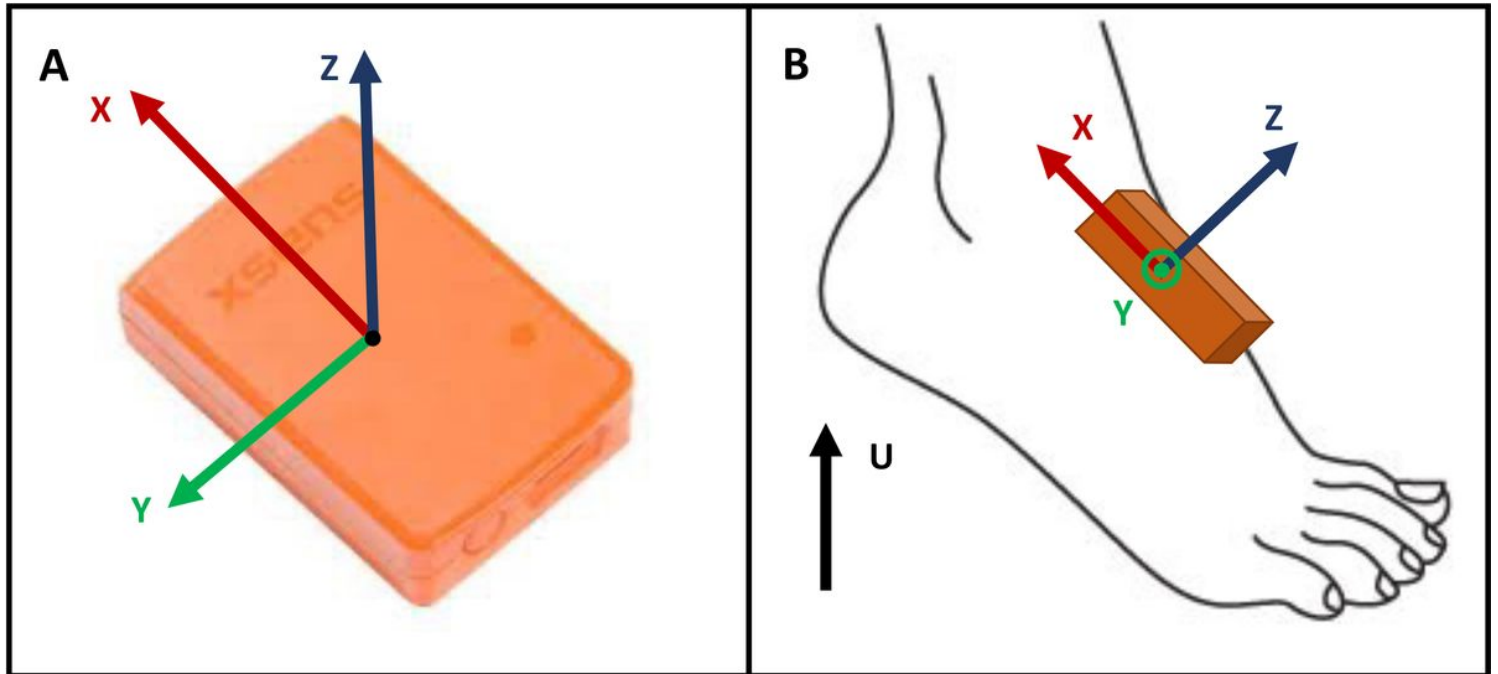


Figure 1

Presentation of the sensor. (A): Tw Awinda XSens® sensor; (B) Definition of the axis for the sensor on the left foot.

experiment can be conducted with or without footwear. In some cases, patients may use a gait aid such as a tripod cane, simple cane, or foot lift. The instructions given are consistent at the beginning of each test. Figure 2 illustrates the gait environment and provides a detailed description of the protocol.

Figure 2 Gait recording protocol. The patient is equipped with two sensors Mtw Awinda XSens[®] placed on the dorsal part of each foot using Velcro bands. Walking is initiated upstream of the active surface of the GR.

Exporting and processing data

For XS recordings, the software XSens MVN studio software (MVN Studio, XSens, the Netherlands) is used to export the nine-dimensional signal (3D accelerations, 3D angular velocities, and 3D magnetic fields). To improve the quality of the signal, a low-pass Butterworth filter of order 8 with a cut-off frequency of 14Hz is applied, in addition to the Kalman filter (XSens Kalman Filter, XKF) provided by the manufacturer. This filter setting is consistent with the trends reported in the literature [35].

For GR recordings, the GAITRite[®] processing software is utilized to obtain the initial contact (IC) and final contact (FC) data. If the quality of the walk permits, automatic segmentation is performed. In cases where manual assistance is required, an expert is consulted. In either case, a visual inspection is conducted by the expert from GR signals and videos if available. The expert has the possibility to reject an event if its annotation is deemed "obviously incorrect": an event in the middle of a phase without gyration or GR sensors turned on away from the footprint. Criteria for the exclusion of an experience or stride annotated by the GR are predetermined and outlined below:

- Logistical criteria that can invalidate an experiment: a sensor being misplaced or not recording for more than 0.5 s during the experiment, inability to export or corruption of a data file, or the subject's inability to complete the entire mat crossing.
- Qualitative criteria that invalidate a GR event: an event partially outside the mat, an event detected too close to the end of the recording (duration less than the average duration of a stride), or obvious visual errors identified by the expert.

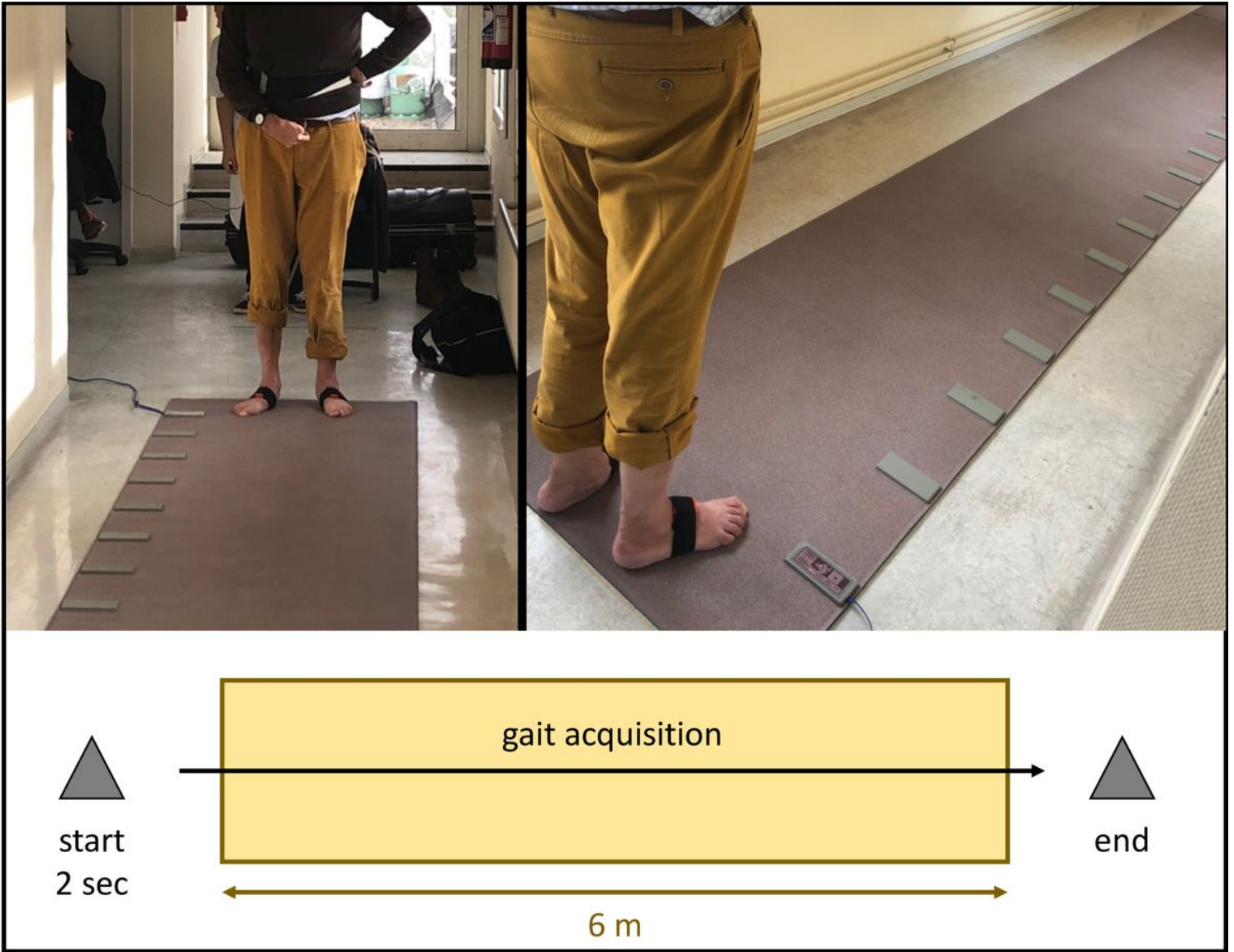


Figure 2

Gait recording protocol. The patient is equipped with two sensors Mtw Awinda XSens® placed on the dorsal part of each foot using Velcro bands. Walking is initiated upstream of the active surface of the GR.

Data of interest

Based on the axes shown in Figure 1, our algorithm focuses on two pre-processed signals. The first signal is the absolute norm of the total jerk free from acceleration, which is obtained from the values of free acceleration:

$$\|\mathbf{j}_{\text{tot}}\| = \sqrt{\left(\frac{d\text{freeAcc}_x}{dt}\right)^2 + \left(\frac{d\text{freeAcc}_y}{dt}\right)^2 + \left(\frac{d\text{freeAcc}_z}{dt}\right)^2}$$

The second signal is the gyration in the sagittal plane directly measured by the sensor: ω_y .

We treat both signals, which are sampled at 100 Hz by the IMUs, as time series. If data is missing, we complete it using quadratic interpolation. The jerk time series and the gyration in the sagittal plane are respectively designed as \mathbf{J} and $\mathbf{\Omega}$ in the following analysis.

Algorithm procedure

First part: stride duration inference with autocorrelation

This section aims to estimate a consistent value for the average duration of a stride. Autocorrelation is a commonly used signal-processing technique that involves cross-correlating a signal with itself. It can be used to estimate the period of an imperfect periodic signal that does not contain a single dominant frequency [36].

We considered the free accelerations and gyrations recorded by foot-level IMUs to be stationary and periodic depending on the regularity of the subject. We computed the autocorrelation for $\mathbf{\Omega}$ and \mathbf{J} components. The estimated stride duration was determined by matching the first autocorrelation peak. We assumed that the expected values of the average stride duration were the same for each foot. To avoid overestimation, we chose the shorter of the two stride estimates. This assumption does not mean that the steps have the same duration and therefore does not erase a potential asymmetry. An illustration of the signals and the peak detection process is provided in Figure 3.

Figure 3 Autocorrelation signal. **A:** control subject. **B:** patient from the EVF cohort. The two graphs on the left show the preprocessed signals of interest for both feet. The righthand graph is the resulting multiparametric autocorrelation for each foot and gives the estimated return value of the duration of a stride (dot line).

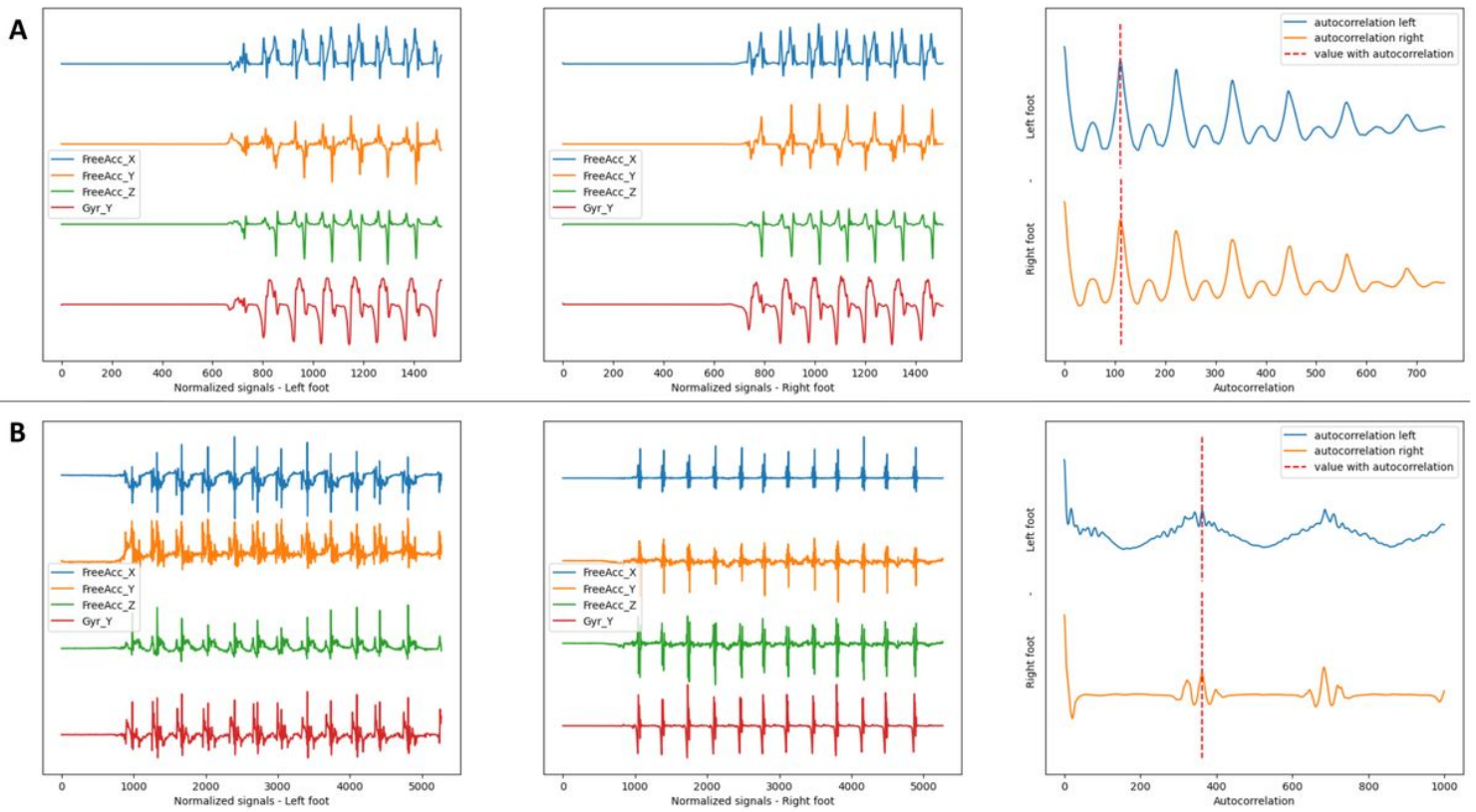


Figure 3

Autocorrelation signal. A: control subject. B: patient from the EVF cohort. The two graphs on the left show the preprocessed signals of interest for both feet. The righthand graph is the resulting multiparametric autocorrelation for each foot and gives the estimated return value of the duration of a stride (dot line).

Second part: reference stride isolation with matrix profile

Once the average duration L of a stride is estimated, we want to find a reference stride. Therefore, the most recurrent pattern of L -size must be extracted from the signal. MP is a recent reference [37, 38] efficient for the pattern extraction task. This time series processing technique uses normalized Euclidean distance to calculate the similarity between subsequences of the original sequence. The resulting output highlights repeating patterns in the data sequence.

To adapt and personalize the pattern detection, so as the start and the end of the pattern corresponds to phenomena of interest, Dau et al. [39] proposed to add an annotation vector (AV). AV is a time series which is explicitly describing the preferred location or expected behavior of the pattern, thus limiting the risk of detecting insignificant patterns [40]. A low value indicates that the subsequence starting at this index is not a valuable pattern, and should therefore be rejected. Conversely, higher values mean that the subsequence at that location should be favored for pattern detection. The combination of AV and MP leads to a corrected matrix profile (CMP).

In our algorithm, we computed a CMP from Ω and a dimensionless AV that favors locations in order to have large variations for \mathbf{J} and Ω in the center of the search window. Our objective was to center the SwP. AV was defined as follows:

$$AV_i = \sum_{k=i+\frac{m}{3}}^{i+\frac{2m}{3}} \frac{\omega_k}{\omega_{max}} + \frac{j_k}{j_{max}}. \quad (1)$$

An illustration of pattern recognition by CMP using the example of gyration is shown in Figure 4.

Figure 4 Corrected Matrix Profile. **A:** control subject. **B:** patient from the EVF cohort. Top: gyration signal (blue) and jerk signal (orange). Bottom: CMP, the red star indicates the minimum value of the CMP and allows the detection of the pattern (black) and its nearest neighbor (red).

Third part: reference stride annotation with DTW

The pattern isolated in the previous section corresponds to a complete stride, probably centered on the SwP. The next step is to annotate this reference stride with the best estimates of TO and HS. To do this, a model stride was used to annotate each reference stride using DTW.

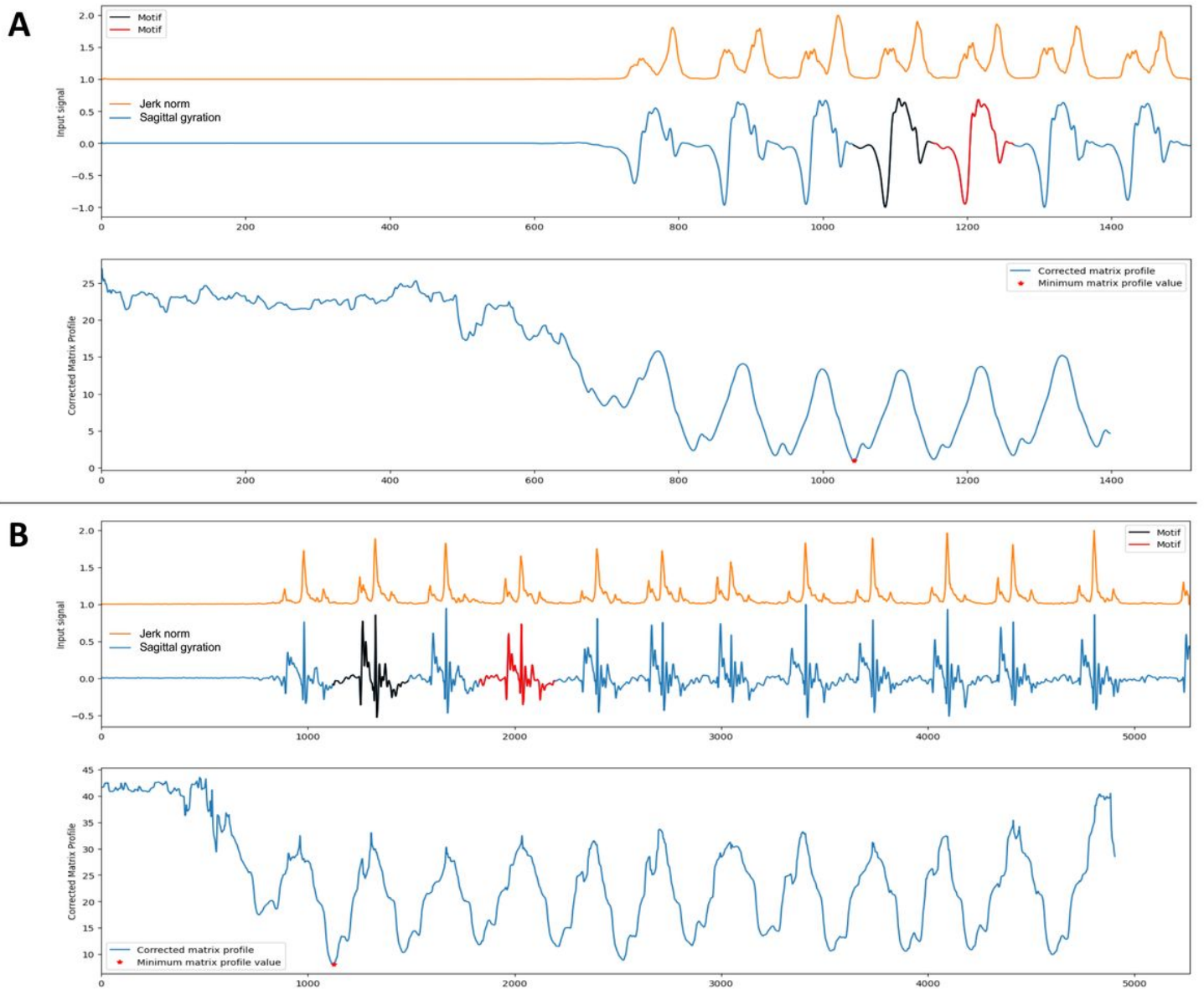


Figure 4

Corrected Matrix Profile. A: control subject. B: patient from the EVF cohort. Top: gyration signal (blue) and jerk signal (orange). Bottom: CMP, the red star indicates the minimum value of the CMP and allows the detection of the pattern (black) and its nearest neighbor (red).

Model Stride. We extracted a "model stride" from our dataset of healthy subjects, which has all 4 stride events annotated. Specifically, TO and HS were annotated with the GR, while FC and IC were annotated with their respective events. FF and HO were estimated and are provided as an indication. The signals of interest corresponding to this stride are illustrated in Figure 5.

Figure 5 Model stride. Stride from a healthy subject used as a model for all detections. **(A):** Gyration (blue) in the sagittal plane. **(B):** Total jerk (blue). For each figure, the 4 events of the stride are represented. TO and HS were given by the GR. FF and HO were visually estimated and given as an indication.

DTW. The Dynamic Time Warping (DTW) algorithm is a distance measure that aligns and transforms two time series through a non-linear transformation to obtain an optimal match between them. Its objective is to determine a measure of their similarity and obtain a matching path between the points called the "warping path". We opted for a multidimensional DTW (mDTW) taking into account both time series \mathbf{J} and $\mathbf{\Omega}$. Following the recommendations of [41], we used a mDTW with dependence between signals, called mDTWd, using normalized Euclidean distance with normalized signals. Because of the probable presence of the SwP in the middle of the reference stride, we used an additional constraint with an Itakura parallelogram with radius $r=2$ [42].

Reference Stride Annotation. To compare and annotate the reference stride with the model stride, we first shifted the model stride to ensure that the SwP was in the same position in both series. We then applied mDTWd to find the optimized path under constraints. Finally, we used this warping path to match the events of both series. We assumed that the last point of the subject's series that matched with the TO point of the model corresponded to the TO estimation, and the first point of the subject's series that matched with the HS point of the model corresponded to the HS estimation. Figure 6 illustrates the annotation protocol and an example of the result.

Figure 6 Annotated reference stride. *Top: healthy subject. Bottom: patient from the EVF cohort.* **A** and **B:** mDTWd matrix between model stride (up) and reference stride (left) signals with the corresponding warping path (white line). **C** and **D:** Annotation of the reference with the 4 GEs. Blue line: jerk. Yellow line: gyration.

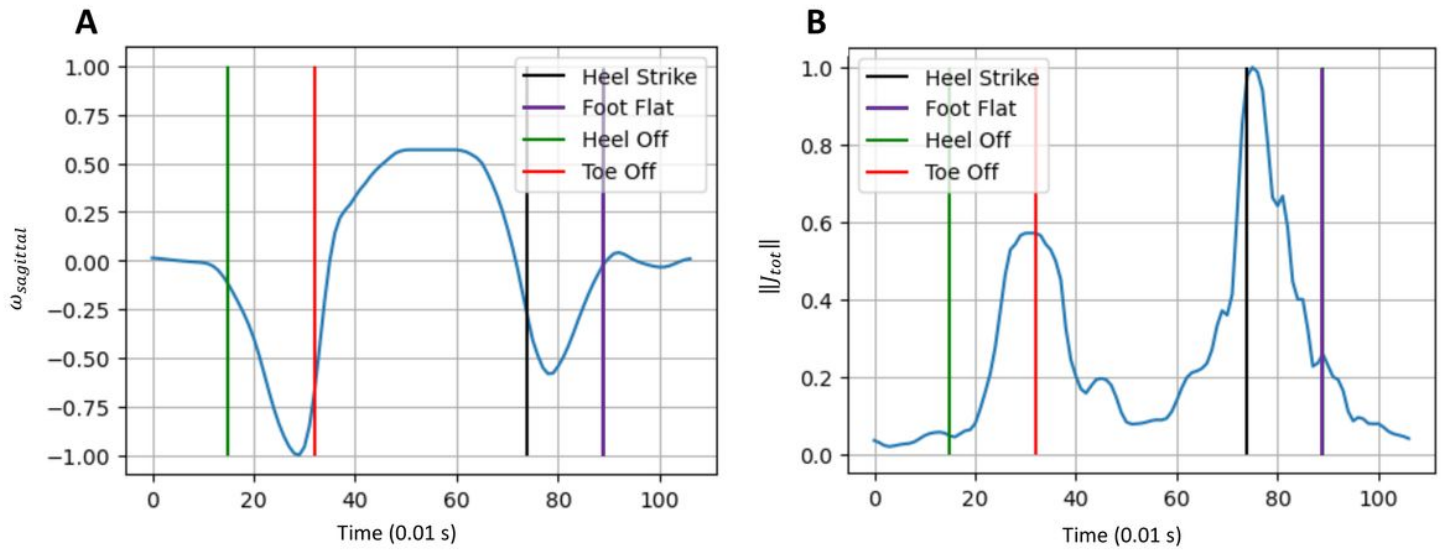


Figure 5

Model stride. Stride from a healthy subject used as a model for all detections. (A): Gyration (blue) in the sagittal plane. (B): Total jerk (blue). For each figure, the 4 events of the stride are represented. TO and HS were given by the GR. FF and HO were visually estimated and given as an indication.

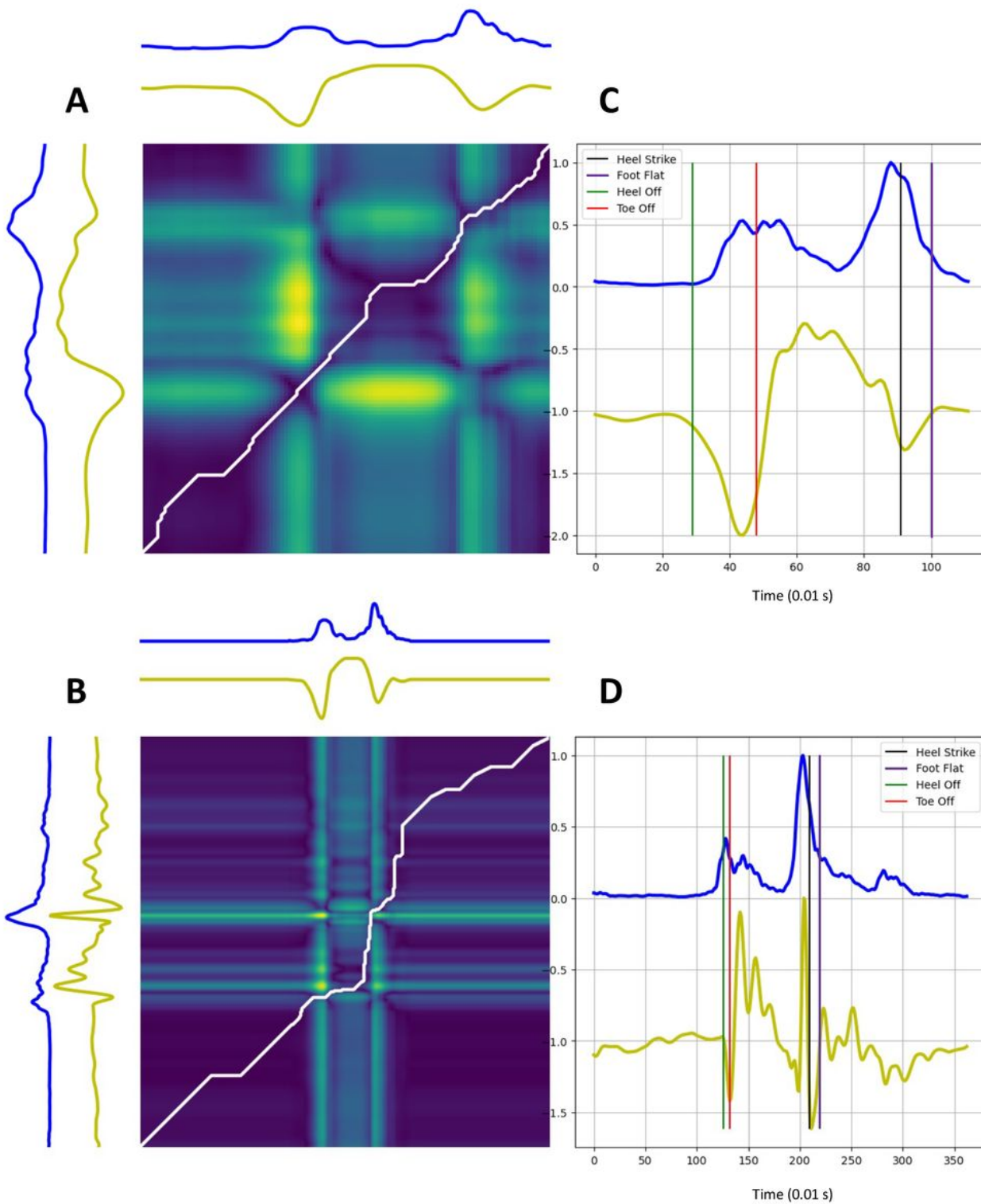


Figure 6

Annotated reference stride. Top: healthy subject. Bottom: patient from the EVF cohort. A and B: mDTWd matrix between model stride (up) and reference stride (left) signals with the corresponding warping path (white line). C and D: Annotation of the reference with the 4 GEs. Blue line: jerk. Yellow line: gyration.

Fourth part: segment the entire walk with a Template-based Detection

The annotated stride obtained at the end of the previous section is used as a reference for the detection of GE throughout the signal using the template-based method. The method used is based on the one described in the article by Dot et al. [10], which uses mDTW on the series while adapting the parameters due to degraded strides: $\lambda = 0.4$ and $\mu = 0.1$. At the end of this final part, **all the detected strides should be completely annotated** with the best findings of TO and HS, as shown in 7.

Figure 7 Final gait segmentation. **A:** control subject. **B:** patient from the EVF cohort. GEs detected by the algorithm were reported on the jerk signal (*top*). Gait phases deduced from GEs were reported on the gyration signal (*bottom*).

Synthesis and technical precisions

An illustration of the whole process is proposed in Figure 8.

Figure 8 Flowchart of the GE detection method. Schematic representation of the 4 parts of the algorithm. The color of the boxes is: red for input data, blue for the corresponding tools and illustrations, brown for intermediate steps, and green for the output result.

The algorithm was implemented with python 3.8, on the PyCharm 2022.3 IDE. In part 2, we used the *compute* function from the Matrix Profile Foundation's python package, with the default parameters. In parts 3 and 4, we used the python *tslearn* package [43] to compute mDTWd.

Performance analysis

The accuracy of the proposed method is assessed by comparing the correctly detected times for HS and TO to the annotations IC and FC of the GR gold standard. The following metrics were used:

- **Events.** As described before, the GEs of interest in the study are TO and HS.
- **Annotated events.** These are the events IC and FC annotated by the GR, considered the Gold Standard.
- **Detected events.** These are the events HS and TO detected by the algorithm between the beginning and the end of the gait experience on the mat.

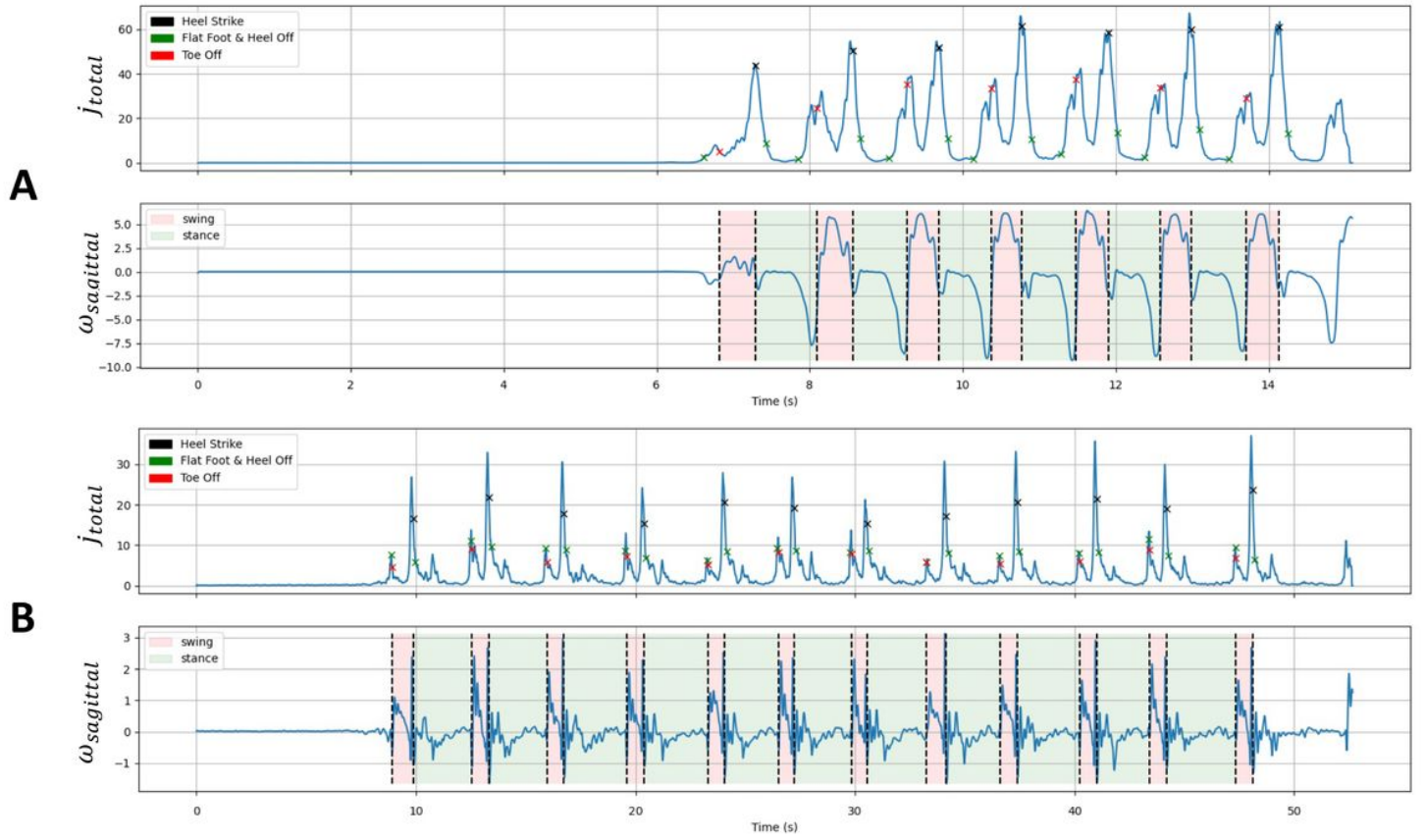


Figure 7

Final gait segmentation. A: control subject. B: patient from the EVF cohort. GEs detected by the algorithm were reported on the jerk signal (top). Gait phases deduced from GEs were reported on the gyration signal (bottom).

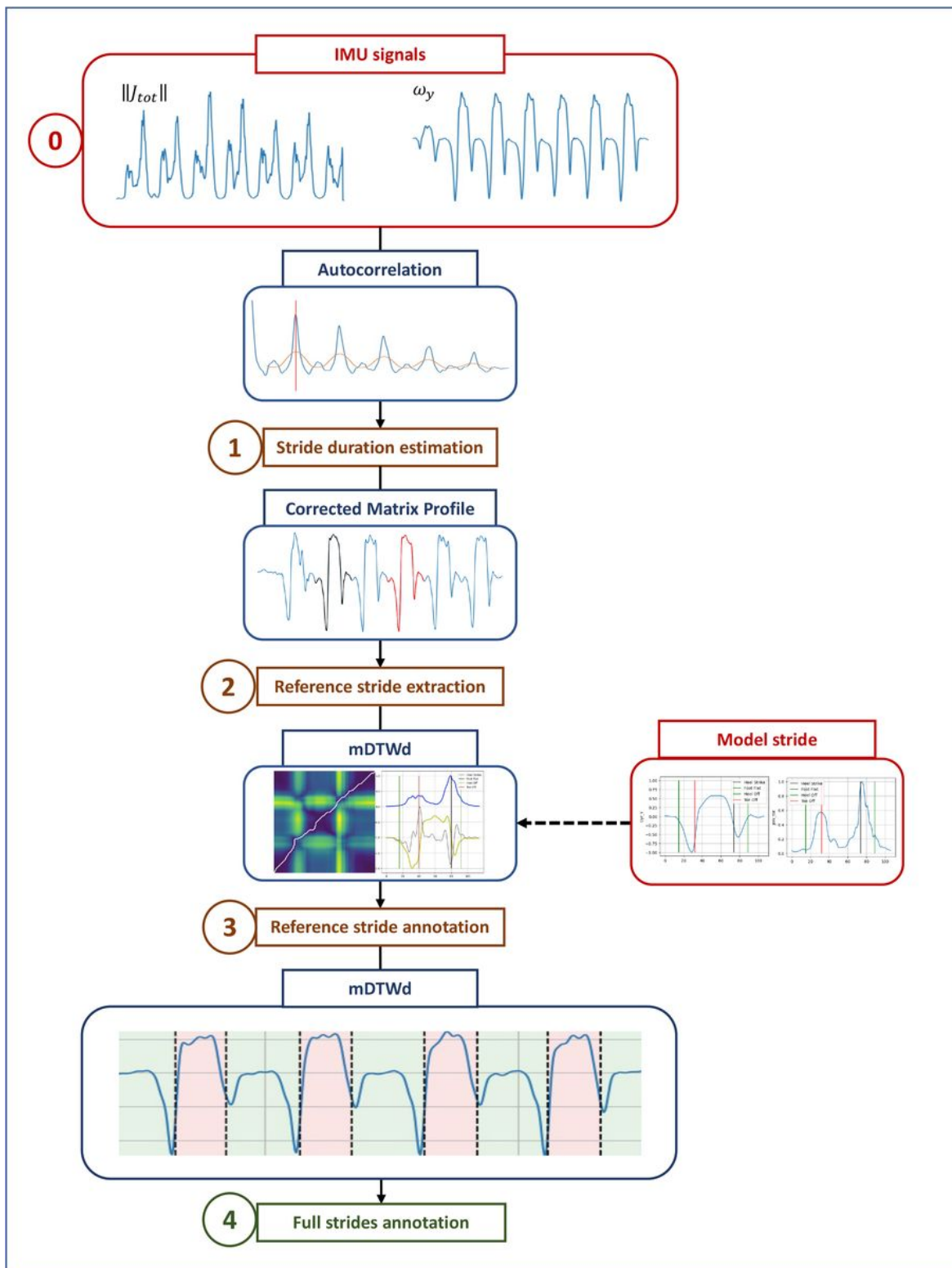


Figure 8

Flowchart of the GE detection method. Schematic representation of the 4 parts of the algorithm. The color of the boxes is: red for input data, blue for the corresponding tools and illustrations, brown for intermediate steps, and green for the output result.

- **Recall (sensitivity).** This is the proportion of events annotated by the GR that have been correctly detected by the algorithm. An annotated event is considered correctly detected if the duration between this annotated event and the nearest detected event of the same nature (TO for FC; HS for IC) does not exceed 20% of the duration of a stride. A detected event can be used only one time. Sensitivity is defined as the ratio between the number of correctly detected annotated events and the total number of annotated events.
- **Precision.** This is the proportion of detected events that effectively correspond to an annotated event. A detected event is considered to be correct if the duration between this detected event and the nearest annotated event of the same nature (FC for TO; IC for HS) does not exceed 20% of the duration of a stride. An annotated event can be used only one time. Precision is defined as the ratio between the number of correctly detected events and the total number of detected events.
- **F1-score.** This is the harmonic mean of precision and recall.

$$F1_{score} = 2 \times \frac{recall * precision}{recall + precision}. \quad (2)$$

- **Δ TO.** For a correctly detected TO event, it is the absolute difference between the corresponding annotated FC and the detected TO.
- **Δ HS.** For a correctly detected HS event, this is the absolute difference between the corresponding annotated IC and the detected HS.
- **Mean Δ HS and Mean Δ TO.** For each type of event, it is the average of the measured absolute differences for the correctly detected and annotated events.

This performance was then evaluated against the performance of the algorithm of Dot *et al.* [10].

Statistical analysis

The main performance metric used to evaluate the method was the F1-score, which is a combined measure of recall and precision. An F1-score of less than or equal to 0.95 was considered indicative of low performance. The second outcome measure was the median absolute error in GE detection compared to the gold standard, which reflects accuracy. The method was compared to the state of the art. For non-

normally distributed data, such as Δ HS and Mean Δ TO, medians and interquartile ranges (IQRs) were reported, and the Wilcoxon-Mann-Whitney test (WMW-test) was used to evaluate the significance of the results. Differences were represented as relative values for visualization. The normality of the data was assessed with the Shapiro-Wilk test. For normally distributed data, means and standard deviations (SDs) were reported. All statistical analyses were computed with R Studio 2023.03.0-386.

Results

Participants

We included 13 CS individuals, 29 MS patients, and 21 EVF patients. The baseline characteristics of the subjects and patients are filled in Table 1.

Table 1 Baseline characteristics of each cohort. For age, height and weight, mean and standard deviations are given. Median and extreme values of EDSS are given for MS patients. There is no validated severity score for the EVF cohort, but it should be noted that the surgical indication for the equine varus foot is given in the most severe cases.

	HS (n = 13)	MS (n = 29)	EVF (n = 21)
Sex (M/F)	6/7	13/16	9/12
Age (years)	26.6 (2.0)	59.2 (10.0)	54.0 (14.8)
Height (m)	1.69 (0.09)	1.69 (9.7)	1.68 (10.9)
Weight (kg)	63.3 (14.8)	67.5 (17.6)	71.2 (14.9)
EDSS	-	6 [2-7]	-

To provide an overview of the quality of the data and gait characteristics, Table 2 presents the number of steps and the mean walking speed for each cohort. Figure 9 illustrates the distribution of walking speed within each cohort.

Table 2 Gait parameters. Number of steps, mean (SD) of gait speed, and median (IQR) number of steps per experience.

	HS (n = 13)	MS (n = 29)	EVF (n = 21)
Speed in m/s (SD)	1.13 (0.11)	0.23 (0.12)	0.28 (0.15)
Total steps	8410	3442	4180
Steps per exp (IQR)	8 (7-8)	27 (22-36)	17 (13-22)

Figure 9 Walking speed distribution for each cohort. Dot lines represent mean values.

Figure 10 provides a detailed overview of the recorded dataset that is utilized in the subsequent analyses (rules are specified in the Methods section).

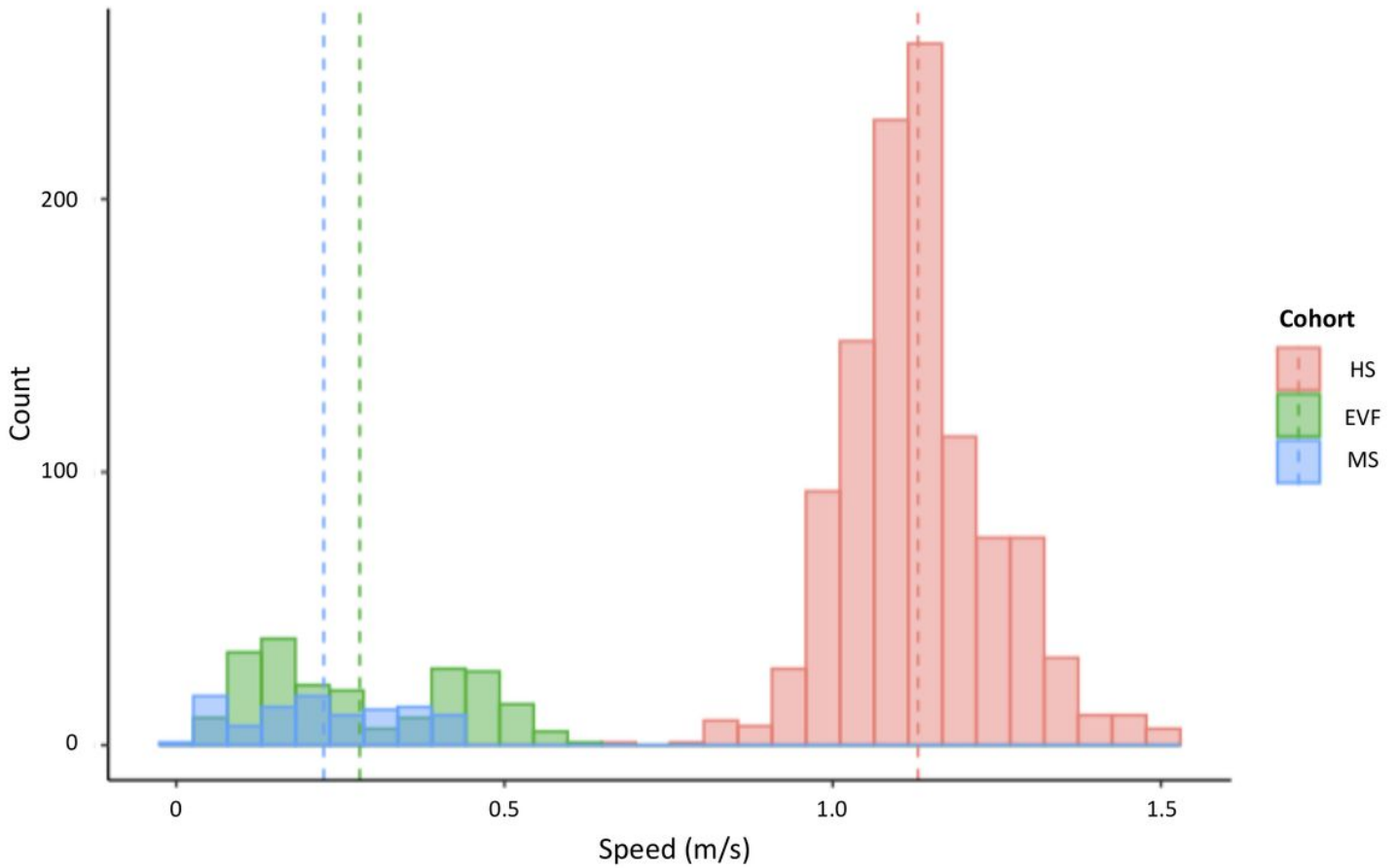


Figure 9

Walking speed distribution for each cohort. Dot lines represent mean values.

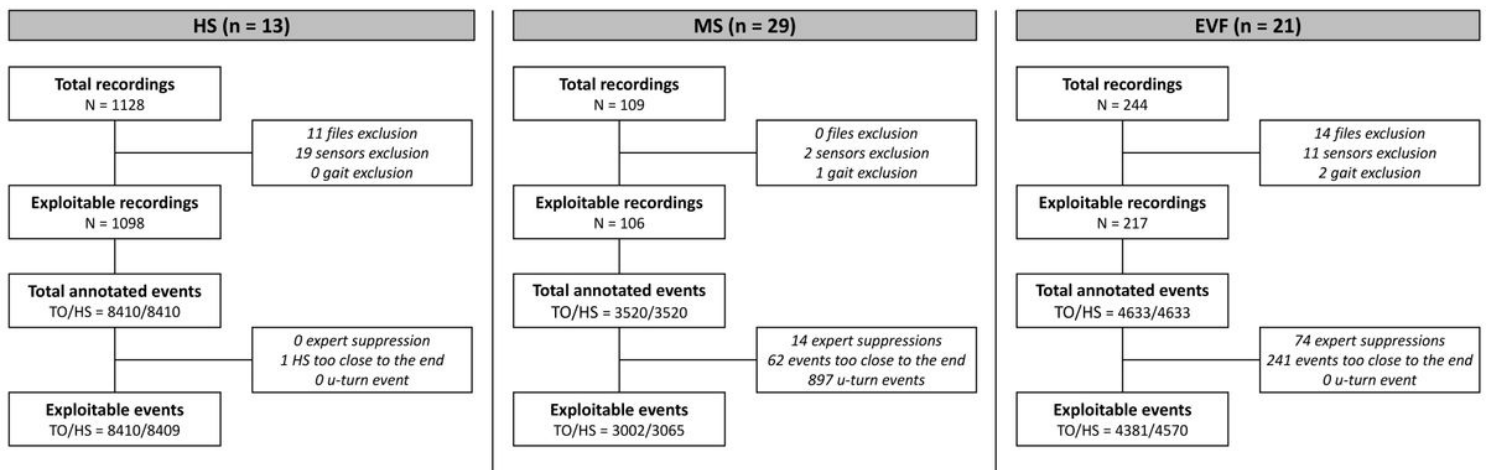


Figure 10

Flowchart of the data collected and analyzed in the study. Rules for deleting and correcting data are provided in Methods.

Figure 10 Flowchart of the data collected and analyzed in the study. Rules for deleting and correcting data are provided in Methods.

Performance and accuracy of the detection method compared to Gold-Standard

The results of the detailed algorithm are presented in Table 3. For the HS cohort, the F1-score was 100%, indicating perfect and exact detection of all strides. Among the well-detected annotated strides, the median Δ TO was 8 ms (IQR [3-15] ms), and the median Δ HS was 7 ms (IQR [3-12] ms). For the MS cohort, the F1-score was 99.4%, with a recall of 99.7% and a precision of 99.2%. The median Δ TO was 23 ms (IQR [10-50] ms), and the median Δ HS was 15 ms (IQR [7-30] ms). For the EVF cohort, the F1-score was 96.3%, with a recall of 96.7% and a precision of 96.0%. The median Δ TO was 27 ms (IQR [15-48] ms), and the median Δ HS was 25 ms (IQR [10-50] ms).

Table 3 Δ TO and Δ HS of our main algorithm for each cohort. All the results are given in milliseconds.

	CS (n = 16819)	MS (n = 6067)	EVF (n = 8951)
F1	100	99.4	96.3
Recall (%)	100	99.7	96.7
Precision (%)	100	99.2	96.0
TO events	8410	3002	4381
Median Δ TO [IQR]	8 [3-15]	23 [10-50]	27 [15-48]
HS events	8409	3065	4570
Median Δ HS [IQR]	7 [3-12]	15 [7-30]	25 [10-50]

The boxplot of Δ HS and Δ TO for the correctly detected and annotated steps of each cohort are presented in Figure 11. The details for each patient or subject included in the study are provided for illustrative purposes in the Supplementary materials [see Additional file 1].

Figure 11 Boxplot of Δ HS and Δ TO. Each dot represents a correctly detected and annotated step.

More detailed histograms are displayed in Figure 12.

Figure 12 Histograms of Δ HS (A, B and C) and Δ TO (D, E and F) for each cohort. Dot lines represent the mean error.

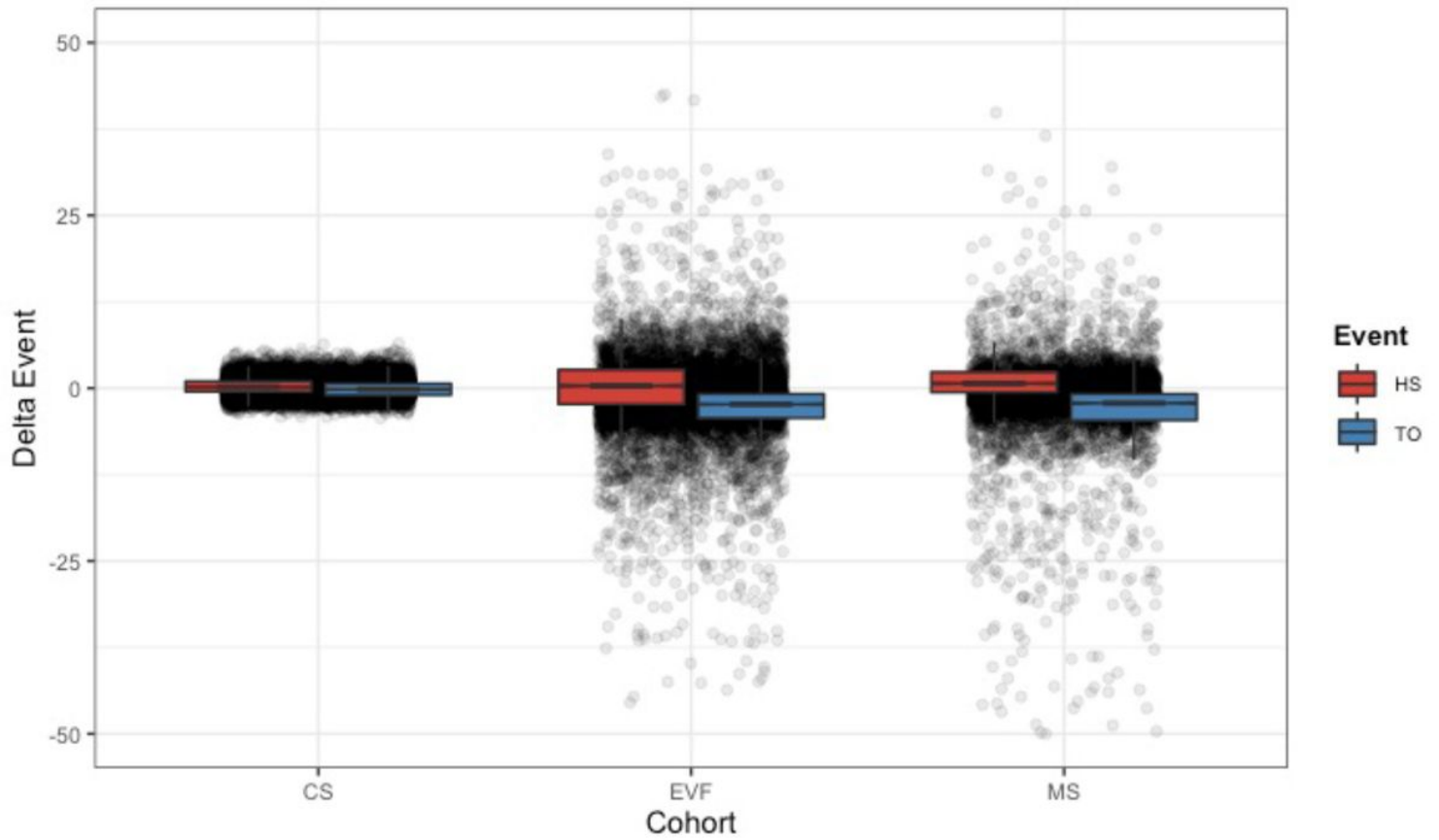


Figure 11

Boxplot of Δ HS and Δ TO. Each dot represents a correctly detected and annotated step.

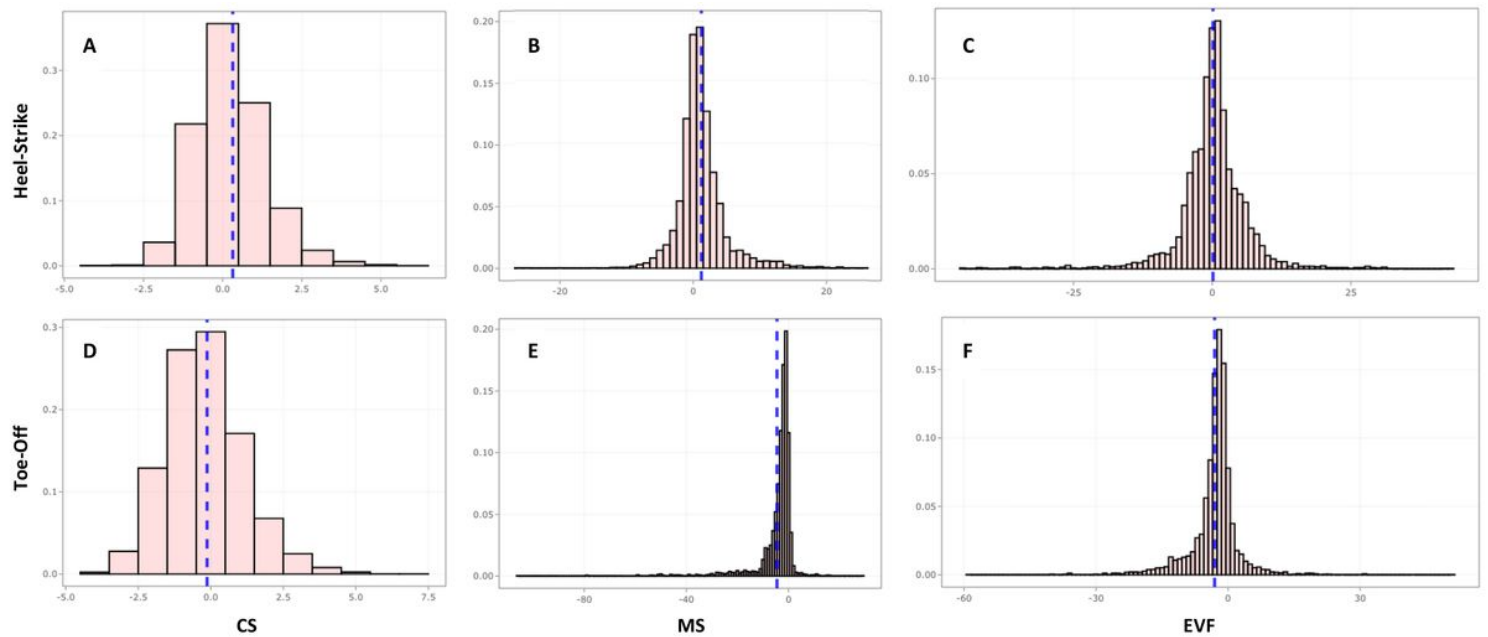


Figure 12

Histograms of Δ HS (A, B and C) and Δ TO (D, E and F) for each cohort. Dot lines represent the mean error.

Performance and accuracy of the detection method compared to State-Of-The-Art

The recently validated Dot [10] algorithm uses the same protocol and the same sensor position, which allows us to use it as a reference to test the results of our algorithm. We applied it to our data set. For CS, the F1-score was unchanged at 100%. The median absolute error for TO was 13 ms (IQRs [7-22] ms) and the median absolute error for HS was 10 ms (IQRs [5-18] ms), which was significantly poorer than our performance (p-value < 0.0001). For MS and EVF, the F1-scores were satisfactory (< 95%) and the median deviations for HS and TO were significantly worse than for our algorithm (p-value < 0.0001). All the results and tests are reported in Table 4.

Table 4 Δ TO and Δ HS of state-of-the-art algorithm for each cohort. All the results are given in milliseconds. When displayed, p-value is the result of the WMW-test with our full algorithm. F1-scores lower than 95% and p-values lower than 0.05 are displayed in bold.

	CS		MS		EVF		
	Value	<i>p-value</i>	Value	<i>p-value</i>	Value	<i>p-value</i>	
Dot 2020[10]	F1-score (%)	100	-	99.1	-	95.7	-
	Recall (%)	100	-	99.4	-	96.1	-
	Precision (%)	100	-	98.8	-	95.4	-
	Mean Δ TO [IQR]	13 [7-22]	< 0.0001	15 [7-53]	< 0.0001	20 [8-68]	< 0.0001
	Mean Δ HS [IQR]	10 [5-18]	< 0.0001	23 [8-66]	< 0.0001	43 [17-82]	< 0.0001

Ablation study

To assess the necessity of the mathematical tools used in parts 2 to 4, we implemented alternative algorithms that either removed these tools or replaced them with simpler ones. We then compared the results obtained with our original algorithm using a WMW-test. We present here 3 of the alternative algorithms that were tested.

- **Test 1: without Jerk signal.** Only the gyration signal was considered for the whole protocol.
- **Test 2: without MP.** We replaced the pattern detection with the MP algorithm with a random selection of a portion of the signal of the same duration, located between the beginning and the end of the gait on GR to ensure that a walking period was selected.
- **Test 3: without DTW.** We replaced the DTW-based method used for annotating the reference stride in part 3 with a correlation optimization method.

Similarly, for part 4, the stride detection on the entire signal was performed solely using correlation without any readjustment by DTW.

Table 5 summarizes the results obtained, clearly demonstrating the relative importance of each of the tools used.

Table 5 Δ TO and Δ HS of alternative algorithms for each cohort. All the results are given in milliseconds. When displayed, p-value is the result of the WMW-test with our full algorithm. F1-scores lower than 95% and p-values lower than 0.05 are displayed in bold.

	CS		MS		EVF		
	Value	<i>p-value</i>	Value	<i>p-value</i>	Value	<i>p-value</i>	
Test 1	F1-score (%)	100	-	99.1	-	95.7	-
	Recall (%)	100	-	99.4	-	96.1	-
	Precision (%)	100	-	98.8	-	95.4	-
	Mean Δ TO [IQR]	8 [3-15]	0.801	30 [13-77]	< 0.0001	31 [17-70]	< 0.0001
	Mean Δ HS [IQR]	8 [3-18]	< 0.0001	19 [8-44]	< 0.0001	38 [15-80]	< 0.0001
Test 2	F1-score (%)	56.4	-	49.2	-	57.2	-
	Recall (%)	56.9	-	48.6	-	57.1	-
	Precision (%)	55.9	-	49.6	-	57.4	-
	Mean Δ TO [IQR]	17 [7-71]	< 0.0001	50 [18-177]	< 0.0001	58 [23-177]	< 0.0001
	Mean Δ HS [IQR]	13 [5-67]	< 0.0001	34 [10-166]	< 0.0001	60 [20-171]	< 0.0001
Test 3	F1-score (%)	97.9	-	98.2	-	95.2	-
	Recall (%)	97.9	-	98.6	-	95.5	-
	Precision (%)	97.9	-	98.0	-	94.9	-
	Mean Δ TO [IQR]	33 [15-90]	< 0.0001	42 [18-90]	< 0.0001	57 [27-100]	< 0.0001
	Mean Δ HS [IQR]	33 [13-67]	< 0.0001	32 [14-73]	< 0.0001	57 [25-107]	< 0.0001

Discussion

Gait analysis using IMU has gained widespread popularity, and several algorithms have been developed and demonstrated their efficacy in detecting gait events (GEs) of healthy individuals [13, 24, 44, 4]. In clinical settings, measuring gait performance provides valuable additional information about walking activity and spontaneous gait characteristics, such as in the follow-up of neurological patients [18, 5, 45] or in preoperative examinations [46, 47]. While some teams use only trunk wearable sensors that provide global features such as smoothness [48], a more precise analysis requires GE detection, which can be done with two separate IMUs on each lower limb [47].

Our algorithm provides automated and reliable GE detection, which is effective not only for healthy subjects but also for pathological gaits (precision \geq 95%, recall \geq 95%, and F1-score \geq 95%). Other previously published techniques have shown

similar F1-scores (Table 6). Hidden-Markov-Model [25], wavelet transform [49], and some rule-based methods have been shown to be effective among these techniques.

Table 6 Δ Start (IC or HS) and Δ End (FC or TO) reported in the literature for healthy subjects and pathological gaits.

Publication	Subjects	F1-score (%)	Δ Start (ms)	Δ End (ms)
Dot et al. 2020 [10]	Healthy	99	15 (18)	16 (13)
Flood et al. 2020 [50]	Healthy	99	16 (7)	40 (16)
Romijnders et al. 2021 [22]	Elderly	100	32	29
	Hemiparetic	100	31	40
	PD	100	33	40
Perez-Iribarra et al. 2020 [51]	Healthy	99	75 (40)	29 (24)
	Hemiparetic	97	68 (42)	52 (39)
	Myelopathic	96	58 (43)	54 (41)
Trojaniello et al. 2014 [26]	Elderly	100	10	20
	Hemiparetic	100	17	21
	PD	100	15	22
	Choreic	100	12	18
Ji et al. 2019 [49]	Healthy	≥ 95	60	20
	Hemiparetic	≥ 95	40	180
Vienne-Jumeau et al. 2020 [28]	Healthy	100	15 (7)	19 (9)
	WA pMS*	99	100 (60)	50 (40)
	NA pMS**	99	60 (70)	30 (40)
Storm et al. 2018 [52]	WA pMS*	-	60 (20)	100 (50)
	NA pMS**	-	70 (30)	100 (30)

* WA-pMS: pMS needing a walking aid // ** NA-pMS: pMS not needing a walking aid.

Regarding the median time error between detected events and GR annotated events, our method demonstrates results of below 10 ms in healthy subjects, which is consistent with the latest algorithms [50, 49, 22], including Deep Learning algorithms [23]. In MS and EVF pathological subjects, our results show moderate impairment and give acceptable results centered around 20 ms. However, most existing algorithms are flawed when analyzing pathological gaits in some neurological pathologies such as multiple sclerosis [28] and hemiplegic patients [47]. At last, some methods require training phases for each patient that may require additional equipment [28]. Although step detection seems to be performant for pediatric hemiplegic patients [53], it remains difficult for post-stroke hemiparetic patients [54].

Our algorithm is built on a Template-Based Approach that has already been successfully applied [29]. Until now, this approach required the implementation of step dictionaries that were not efficient enough for pathological gaits. Additionally, when these dictionaries were customized [28], they required the joint use of an instrumented mat as GR during the training phase, which compromised clinical

deployment. To overcome this, our method extracts the template directly from each record. The results show that CMP described by VanBenschoten *et al.* [33] may be an important part in increasing the precision and accuracy of detection. The addition of DTW, often used in HMM, has also increased detection performance as it does not depend on the time factor but only on the similarity of the signals [30]. Dot *et al.* [10] showed that using a single template based on gyration signals and associated with non-linear deformations may be sufficient to model the gait of healthy subjects, and our algorithm is consistent with this result. However, whereas Dot *et al.* did not efficiently detect GEs in highly pathological gaits, our method maintains satisfactory results in neurological patients. As suggested by [31], the use of mDTWd has shown better efficiency.

Our study may have some limitations. Firstly, only short straight-line gait has been studied, whereas the u-turn may provide valuable information in monitoring neurological pathologies [55, 56]. Secondly, the experiments took place in a safe, hospital environment. Even if these two conditions are suitable for the examination of gait in daily clinical practice, they do not reflect the patient's gait in a free environment and may have limitations when transposing the method to real-life gait recordings. Finally, the gold standard we used has limitations in analyzing highly pathological steps. The GR automated step detection is ineffective since it relies on a well-paced right-left alternation respecting a median line. Even the manual annotation of steps via the GR software with a video fails when patients do not have a classic HS-TO stride sequence. For instance, in the case of foot drop, the stride's initial contact will not always be the HS but could be a "Toe-Strike." Additionally, in some patients, the foot does not leave the ground due to an important motor deficit, yet the foot moves and no longer really carries the body's load. Bruening *et al.* suggests using different algorithms depending on the gait pattern [57]. For us, it is essential that one reproducible algorithm allows step detection for all gait patterns, particularly for longitudinal follow-up of operated patients, as surgery may significantly alter their gait. Furthermore, this raises the question of the step's definition. While some teams consider Initial Contact and Final Contact as genuine GEs, we prefer to consider HS and TO, which define step stability during the StP. Thus, for foot drop, Toe-Strike could be considered part of the SwP since the patient has not yet stabilized their foot on the ground.

Considering these factors, template analysis by IMU complements contact analysis by instrumented mats or force platforms.

Another issue to consider is the localization of wearable sensors for gait analysis [9, 58]. Trojanello *et al.* and Romijnders *et al.* use a shank sensor, which may be more sensitive to the anterior-posterior acceleration movement during the static phase, for which the foot sensor does not provide any information [26, 23]. This location may be more suitable for detecting gait events. However, for the analysis of step width and asymmetry, the sensor located on the foot will be more sensitive to variations and thus provide more relevant information. It is therefore a compromise between detecting gait events and analyzing gait parameters.

Conclusion

Our Adaptive Non-Linear Approach to Step Detection using IMU has proven to be effective in analyzing the gait of healthy individuals and some pathological gait, without the need for an annotated dictionary or the use of a gait recognizer. This innovative tool has the potential to enable real-time gait analysis of neurological patients and can be used as a routine clinical tool throughout their follow-up. Our next objective is to provide an instantaneous gait analysis that can be deployed in clinical routines.

List of abbreviations

The following abbreviations are used in this manuscript:

IMU	Inertial Measurement Units
GE	Gait event
HO	Heel-Off
TO	Toe-Off
HS	Heel-Strike
FF	Foot-Flat
StP	Stance Phase
SwP	Swing Phase
DTW	Dynamic Time Warping
mDTW	multiparametric Dynamic Time Warping
mDTWd	multiparametric Dynamic Time Warping with dependence
MP	Matrix Profile
CMP	Corrected Matrix Profile
AV	Annotation Vector
CS	Control Subject
MS	Multiple Sclerosis
EVF	Equino Varus Foot
XS	MTw Awinda XSens [®]
GR	GAITRite [®] walkway
IC	Initial Contact
FC	Final Contact
IQR	Inter Quartile Range
SD	Standard Deviation

Availability of data and materials

The datasets generated for this study are available on request to the corresponding author.

Competing interests

The authors declare that they have no competing interests.

Author's contributions

CV conceived the study and the statistical analysis and wrote the manuscript. NE conceived the study and wrote the manuscript. LO conceived the study and edited the manuscript. DR conceived the study and edited the manuscript. All authors contributed to refining the study protocol and approved the final manuscript.

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Author details

¹Université Paris Saclay, Université Paris Cité, ENS Paris Saclay, CNRS, SSA, INSERM, Centre Borelli, Gif-sur-Yvette, France. ²Université Paris Cité, Université Paris Saclay, ENS Paris Saclay, CNRS, SSA, INSERM, Centre Borelli, Paris, France. ³Service de Neurologie, Service de Santé des Armées, HIA Percy, Clamart, France. ⁴Service de Chirurgie Orthopédique, Traumatologique et Réparatrice des Membres, Service de Santé des Armées, HIA Percy, Clamart, France. ⁵Ecole du Val-de-Grâce, Service de Santé des Armées, Paris, France.

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Additional Files

Additional figure 1

Figure 13 Boxplot of Δ H_S and Δ T_O for each subject or patient included in the study.

3.2 Le semiogramme

Une fois assurée la segmentation du pas à partir du signal de marche issus des IMUs portés par le sujet, quelle que soit leur dégradation du schéma de marche, il est possible de calculer les indicateurs de caractérisation pertinents en clinique. La difficulté de cette étape réside dans l'accessibilité et la facilité d'utilisation des données obtenues pour le clinicien qui risque d'être noyé sous une multiplicité d'indicateurs indépendants dont la signification n'est pas toujours intuitive. Dans l'objectif de donner au clinicien un rendu visuel facile d'interprétation (paragraphe 2.3), l'utilisation d'un diagramme en radar selon des dimensions formalisées est une approche permettant de compiler plusieurs paramètres interprétables en un seul coup d'œil et pouvant se résumer par une quantité (l'aire du semiogramme) utilisable pour un suivi longitudinal individuel. Nous avons ainsi réparti les paramètres mathématiques en sept critères sémiologiques de la marche que nous présentons sous forme d'un diagramme en radar appelé semiogramme. La vitesse moyenne étant capitale dans l'analyse de la marche elle est représentée par une échelle de couleur. Cet outil a un intérêt important dans le suivi longitudinal des patients souffrant d'une affection chronique altérant la marche telle que la SEP. Nous avons donc décrit et évalué le semiogramme sur les données de patients enregistrés de façon antérieure à notre étude, en comparant l'aire du semiogramme au score EDSS moyen de ces patients (Figure 9).

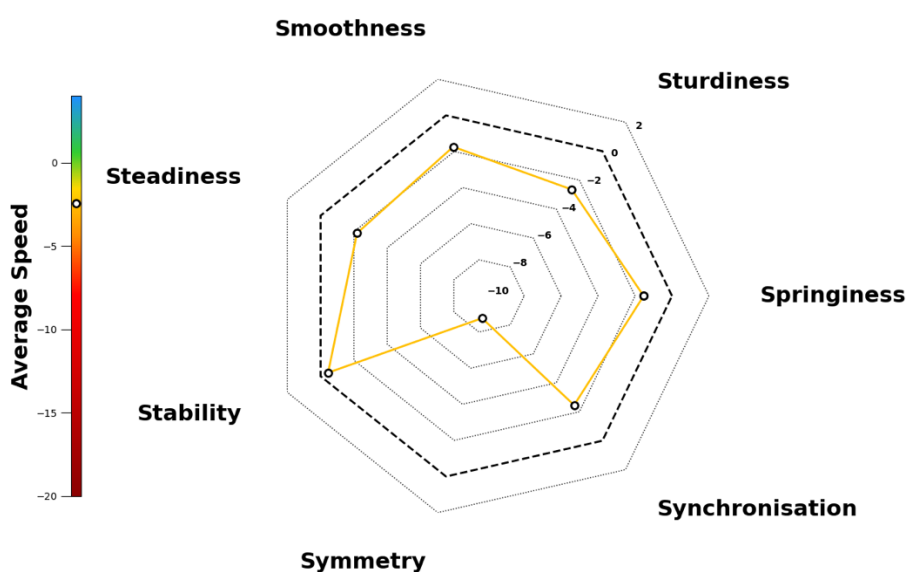


Figure 9 : Exemple de rendu visuel obtenu avec un semiogramme.



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EDITED BY

Luigi Tesio,
Italian Auxological Institute (IRCCS), Italy

REVIEWED BY

Anisoara Paraschiv-Ionescu,
Swiss Federal Institute of Technology Lausanne,
Switzerland
Serap Alsancak,
Ankara University, Türkiye
Roy Müller,
Klinikum Bayreuth GmbH, Germany

*CORRESPONDENCE

Cyril Voisard
✉ cyril.voisard@etu.u-paris.fr

†These authors have contributed equally to this work

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Innovative multidimensional gait evaluation using IMU in multiple sclerosis: introducing the semiogram

Cyril Voisard ^{1,2,*†}, Nicolas de l'Escalopier ^{3,4†}, Aliénor Vienne-Jumeau¹, Albane Moreau¹, Flavien Quijoux¹, Flavie Bompaire^{2,3}, Magali Sallansonnet², Marie-Laure Brechemier², Irina Taifas², Camille Tafani², Eve Drouard², Nicolas Vayatis¹, Damien Ricard^{2,3,5} and Laurent Oudre¹

¹Université Paris Saclay, Université Paris Cité, Ecole Normale Supérieure Paris Saclay, Centre National de la Recherche Scientifique, Service de Santé des Armées, Institut National de la Santé et de la Recherche Médicale, Centre Borelli, Gif-sur-Yvette, France, ²Service de Neurologie, Service de Santé des Armées, Hôpital d'Instruction des Armées Percy, Clamart, France, ³Université Paris Cité, Université Paris Saclay, Ecole Normale Supérieure Paris Saclay, Centre National de la Recherche Scientifique, Service de Santé des Armées, Institut National de la Santé et de la Recherche Médicale, Centre Borelli, Paris, France, ⁴Service de Chirurgie Orthopédique, Traumatologique et Réparatrice des Membres, Service de Santé des Armées, Hôpital d'Instruction des Armées Percy, Clamart, France, ⁵Ecole du Val-de-Grâce, Service de Santé des Armées, Paris, France

Background: Quantifying gait using inertial measurement units has gained increasing interest in recent years. Highly degraded gaits, especially in neurological impaired patients, challenge gait detection algorithms and require specific segmentation and analysis tools. Thus, the outcomes of these devices must be rigorously tested for both robustness and relevancy in order to recommend their routine use. In this study, we propose a multidimensional score to quantify and visualize gait, which can be used in neurological routine follow-up. We assessed the reliability and clinical coherence of this method in a group of severely disabled patients with progressive multiple sclerosis (pMS), who display highly degraded gait patterns, as well as in an age-matched healthy subjects (HS) group.

Methods: Twenty-two participants with pMS and nineteen HS were included in this 18-month longitudinal follow-up study. During the follow-up period, all participants completed a 10-meter walk test with a U-turn and back, twice at M0, M6, M12, and M18. Average speed and seven clinical criteria (sturdiness, springiness, steadiness, stability, smoothness, synchronization, and symmetry) were evaluated using 17 gait parameters selected from the literature. The variation of these parameters from HS values was combined to generate a multidimensional visual tool, referred to as a semiogram.

Results: For both cohorts, all criteria showed moderate to very high test–retest reliability for intra-session measurements. Inter-session quantification was also moderate to highly reliable for all criteria except smoothness, which was not reliable for HS participants. All partial scores, except for the stability score, differed between the two populations. All partial scores were correlated with an objective but not subjective quantification of gait severity in the pMS population. A deficit in the pyramidal tract was associated with altered scores in all criteria, whereas deficits in cerebellar, sensitive, bulbar, and cognitive deficits were associated with decreased scores in only a subset of gait criteria.

Conclusions: The proposed multidimensional gait quantification represents an innovative approach to monitoring gait disorders. It provides a reliable and

informative biomarker for assessing the severity of gait impairments in individuals with pMS. Additionally, it holds the potential for discriminating between various underlying causes of gait alterations in pMS.

KEYWORDS

gait quantification, gait disorders, multiple sclerosis, wearable inertial sensors, inertial measurement unit

1. Introduction

Multiple sclerosis (MS) is a chronic demyelinating disease of the central nervous system that can cause a variety of symptoms, including spasticity, fatigue, loss of balance, sensory deficits, and weakness. These impairments often interfere with gait, with up to 75% of people with MS reporting difficulties walking at some point during the course of their disease (1). Many patients rank complaints such as “heavy legs,” sensations of having to “fight their own leg,” and “running out of energy” as the most debilitating (2). These impairments have a significant impact on the daily activities, social status, and overall quality of life of people with MS and their loved ones.

Day-to-day evaluation of gait disturbances in MS primarily relies on detailed patient interviews and visual observation of walking. The Kurtzke Expanded Disability Status Scale (EDSS), a 0- to 10-point scale, is the main reported outcome measure, determined by gait and functional system (FS) scores, including Pyramidal, Cerebellar, Brainstem, Sensory, Bowel, and Bladder, Visual, Cerebral or Mental, and Other factors. EDSS scores \leq 4.0 are determined by FS scores alone, whereas scores 4.0–9.5 represent both gait abilities and FS scores. However, this scale is criticized for its insensitivity to early alterations and slight changes (3), as well as its high inter-rater variability (4). To complement clinician assessment, patient-reported outcomes such as the Multiple Sclerosis Walking Scale-12 (MSWS) can inform mobility limitations (5). The MSWS is a 12-item measure of the impact of MS on walking, rated on a scale from 1 to 5, and reported from 0 to 100. However, patient-reported outcomes are subjective and may be confounded by psychosocial factors, disease-related cognitive impairments, unblinding and “expectation bias,” or “response shift” in longitudinal evaluations (6).

Objective gait can be measured in various ways. Stopwatch-timed tests, such as the timed up-and-go test or the 25-foot walk test, are considered the best objective measure of walking disability for MS (5) and have long been used (7, 8). However, these tests have high intra-subject variability (9) solely on gait performance, without taking into account its quality status. From a semiological standpoint, the visual qualitative description of gait disorders has long been and still remains the primary tool for clinicians. However, in some progressive diseases such as multiple sclerosis, gait degradation may be quantified at an infra-clinical scale: visual evaluation may lack sensitivity for small changes and cannot reliably capture the progression from one consultation to another (10). To refine the analysis, laboratory-based measurements are powerful tools that can track gait disturbances early on in clinically isolated syndromes (11). However, these tools are cumbersome and

expensive, and cannot be implemented within the time constraints of a routine clinical examination.

Inertial measurement units (IMUs) are small, lightweight wearable sensors that can be used to assess gait in MS both in routine clinical practice and at home for long-term physiological gait assessment (7, 12–19). They have also been found useful to detect early changes in MS with clinically isolated syndromes (13, 20), and parameters such as speed, step length, and step time are correlated with the severity of the disease (16). Longitudinal monitoring of gait and balance identifies changes in disease progression that are modifiable with physical rehabilitation (21). The use of IMUs to study the impact of spasticity on MS gait has received increased support with the development of related treatments (22–24). Nevertheless, other causes of gait deterioration (ataxia, sensitive deficit, vestibular deficit, and cognitive deficit) have been little investigated.

In this study, we present a simple visual tool computed from IMU signals, called a semiogram, which enables a qualitative evaluation of gait for the longitudinal monitoring of patients with progressive MS (pMS), characterized by gradual accrual of disability independent of relapses over time, and including primary and secondary progressive MS. The primary objective of this tool is to assist the clinician in quantifying the degradation or improvement of each semiotic criterion of gait activity from one consultation to another in a patient. This study details the construction of the semiogram, evaluates its reliability among a group of pMS patients and healthy control subjects (HS) measured at different times, and finally shows that this representation is consistent with disease severity and functional status scores, such as MSWS, EDSS, and EDSS FS values, in individuals with pMS.

2. Methods

2.1. Cohorts

Participants with pMS were consecutively recruited from the outpatient clinic of Percy Hospital (Clamart, France) between June 2018 and September 2018. HS participants were recruited from the hospital and research unit staff between June 2018 and September 2018. All participants were followed for 12 months. The inclusion criteria for the pMS cohort were an age of at least 18 years, a diagnosis of primary progressive or secondary progressive MS according to the 2010 International Panel criteria (25), the ability to walk two sets of 10 m forward and back with a U-turn, and no other condition than neurological one linked to pMS that affects gait. The only exclusion criterion was pregnancy. Inclusion criteria

for the HS cohort were no report of falls in the past 5 years before inclusion [falls were defined as events that lead the standing or walking individual to a lower level on the ground unintentionally, without being externally pushed or pulled, regardless of whether an injury is sustained (26)], no disease that could affect walking and to be considered healthy after a clinical examination by medical doctors among investigators. All participants provided written informed consent before inclusion. The study protocol was conducted according to the Helsinki principles and was approved by Ethics Committee “Protection des Personnes Nord Ouest III” (ID RCB: 2017-A01538-45).

2.2. Gait measurement protocol and processing

2.2.1. Protocol

Gait was measured by using three 3-D accelerometers (MTw Awinda XSens[®], 100-Hz sampling frequency) positioned on the lower back (L4-L5 vertebrae) and dorsal part of both feet with elastic belts. All participants remained fully clothed and wore their own shoes, which remained consistent between all visits. Participants who used bracing or assistive devices for safety during gait used them during all walking trials. Each gait measurement included two 10-m walks with a U-turn and back, performed at a self-selected comfortable speed on an unlevelled floor. The start of each walking trial was verbally signaled by the assessor. The U-turn was to be performed behind a marked line on the ground, and both the strategy and side of the U-turn were left up to the patient's discretion. Patients were assessed three times at 6-month intervals. The protocol and sensor placement are shown in [Figure 1](#).

2.2.2. Gait detection

Gait detection was performed using an automated detection algorithm that was previously described (27). The algorithm combined pattern extraction and temporal dilation methods to detect gait events from the foot-level sensor data. Firstly, patterns corresponding to steps in multidimensional time series were extracted from foot-level sensors. Then, the algorithm accurately determined the two important walking events—Initial Contact (IC) and Final Contact (FC).

2.2.3. U-turn detection

The U-turn was identified from the whole signal using a previously validated automated method (28). In summary, the method integrated the angular velocity around the craniocaudal axis derived from the IMU positioned on the lower back to extract the angular position around the craniocaudal axis. During the U-turn, the linear drift was corrected by assuming that the turn begins at 0° and ends at 180°. The method automatically detected inflection points close to these values and defined them as the boundaries of the U-turn. Overall, this automated method was able to accurately delineate the U-turn from the walking signal using IMU data.

2.3. Construction of the semiogram

2.3.1. Inclusion and computation of potential parameters

The selection of parameters included in the multidimensional score was initially based on a systematic review of the use of inertial sensors in neurological populations, conducted by Vienne et al. (7), this selection was then complemented by more recent parameters validated in the literature (29–34). As recommended in this systematic review, walking speed was initially considered a global criterion for assessing gait quality. Then, the semiological analysis of walking was segmented into seven gait criteria that are commonly assessed in the fields of neurology, physical medicine, rehabilitation, gerontology, and rheumatology. The seven criteria were: springiness, smoothness, steadiness, sturdiness, stability, symmetry, and synchronization. To develop the multidimensional score, we selected the most relevant parameters for each of the seven gait criteria based on the systematic review, updated according to the literature. The calculation methods for each parameter were derived from the literature and are explained below. The use of consistent definitions and methods ensured the reliability and validity of the multidimensional score across different studies and populations.

- **Average speed:** refers to gait velocity.
 - *Velocity (V)*. It was defined as the total length (20 m) divided by the total duration of the walking test (from the first to the last gait event) after the exclusion of the U-turn.
- **Springiness:** refers to gait rhythmicity. Two parameters were selected for inclusion:
 - *Stride time (StrT)*. This allows for capturing springiness during straight walking. It was defined as the time between consecutive initial contact (IC) of the same foot, averaged across all strides within the trial after the initiation step, and excluding the U-turn period. This definition ensures that only valid strides are included in the calculation of stride time.
 - *U-turn time (UtrT)*. This allows for capturing springiness during U-turn. It was defined as the duration of the turn that was segmented using the method described above.
- **Smoothness:** refers to gait continuousness or non-intermittency (35). Three parameters were selected for inclusion, as recommended by Melendez-Calderon et al. (29):
 - *Spectral arc length (SPARC – G)*. It measures the smoothness of the trunk signal by analyzing its frequency components by calculating the arc length of the Fourier magnitude spectrum of the gyration signal within an adaptive frequency range. This index quantifies movement intermittencies independently of its amplitude or duration (29, 30, 32–34). The computation procedure was performed according to the method described by Melendez-Calderon et al. (29).

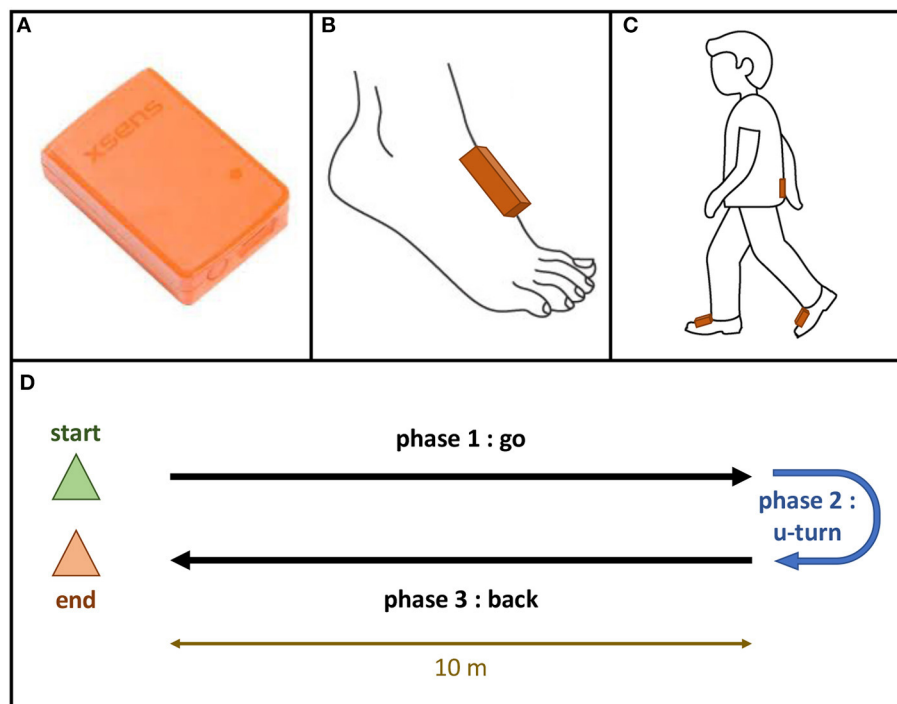


FIGURE 1

Gait protocol. (A) mTw Awinda XSens® sensor; (B) Position of the sensor on the dorsal part of each foot; (C) Position of the sensors using Velcro bands: one sensor on each foot, one sensor in the lower back (vertebra L5); (D) Gait trial: 10-meter walk test with a U-turn.

- *Log dimensionless jerk (LDLJ – A)*. This quantifies how quickly the acceleration of the signal is changing over time, taking into account amplitude and duration. We computed the anteroposterior jerk of the trunk sensor, during straight-walking phases as the variation of the anteroposterior acceleration (35). The computation procedure was the same as described in Melendez-Calderon et al. (29). A longer spectrum indicates a rougher signal.
- **Steadiness:** refers to gait regularity. Four parameters were selected for inclusion:
 - *Variation coefficient of step time (CV_{StrT})*. This allows for capturing springiness variation along the test. It was defined as the standard deviation of the vector of stride times divided by its average.
 - *Variation coefficient of double stance time (CV_{dstT})*. This allows for capturing synchronization variation along the test. It was defined as the standard deviation of the vector of double stance times divided by its average.
 - *Craniocaudal step autocorrelation coefficient ($P1_{aCC}$)*. It evaluates how similar the signal of the trunk is at a time delay corresponding to the duration of a step. This similarity is quantified by the first peak of the craniocaudal autocorrelation coefficient of the lower back.
 - *Craniocaudal stride autocorrelation coefficient ($P2_{aCC}$)*. It evaluates how similar the signal of the trunk is at a time delay corresponding to the duration of a stride.
- This similarity is quantified by the second peak of the craniocaudal autocorrelation coefficient of the lower back.
- **Sturdiness:** refers to gait amplitude. One parameter was selected for inclusion:
 - *Step length ($Stel$)*. It is an indirect indicator of sturdiness that reflects the solidity and robustness of the gait. It was defined as the total length (20 m) divided by the total number of steps after the exclusion of the U-turn.
- **Stability:** refers to gait balance. One parameter was selected for inclusion:
 - *Mediolateral root mean square (RMS_{aML})*. It quantifies the side-to-side movement of the trunk during the test. It was defined as the measure of the dispersion of the mediolateral acceleration of the lower back relative to zero during straight-walking phases.
- **Symmetry:** refers to right/left concordance during gait. Five parameters were selected for inclusion:
 - *Ratio of the step to the stride peak of the craniocaudal correlation coefficient ($P1P2_{aCC}$)*. This quantifies the symmetry of the resultant acceleration at the trunk level during left and right activities. It was defined as the ratio of P1 to P2, P1 and P2 previously defined.

- *Ratio of left and right mean swing times (swTr)*. This quantifies the symmetry of the left and right activities. It was defined as the ratio of the minimum (right or left) of averaged swing time divided by the maximum (right or left) of averaged swing time.
- *Three improved harmonic ratios: anteroposterior (iHR_{aAP}), mediolateral (iHR_{aML}), craniocaudal (iHR_{aCC})*. They evaluate the similarity of the energy distribution as a function of frequency between the left and right limbs. The use of the harmonic ratio to describe gait smoothness was first introduced by Gage (36) and later improved by Pasciuto et al. (37). The iHRs quantify the biphasic and monophasic natures of the signals, which are part of gait symmetry (38). The computation procedure was as described (31). To sum up, for each stride, a fast Fourier transform was performed to draw the Fourier series of the stride. The iHRs were calculated as the ratio of the power of the intrinsic harmonics (even harmonics along the anteroposterior and craniocaudal axes, odd harmonics along the mediolateral axes) to the total power of the signal. The result is a normalized index ranging from 0 to 100%.

- **Synchronization:** refers to inter-limb coordination during gait. One parameter was selected for inclusion:

- *Double stance time (dstT)*: It assesses the synchronization between the lower limbs by quantifying the time during which both feet are in contact with the ground simultaneously. It was defined as the time between the IC of one foot and the FC of the contralateral foot divided by the total time of the cycle time. Two periods of double stance occur during a cycle and are therefore added before division by the total time of the cycle time.

2.3.2. Selection of included parameters based on their reliability

For each parameter, we used a test-retest design to compute intra- and inter-session reliability. Intraclass correlation coefficients (ICCs) and standard error of the mean (SEM) values were calculated for all participants (both pMS and HS). To determine the level of agreement, we followed previous studies (39, 40). ICCs ≥ 0.75 were considered excellent, 0.4–0.75 were considered moderate to high, and ≤ 0.4 were considered low. Parameters with ICCs of 0.4 or lower were removed from the calculation of the gait criteria partial scores.

2.3.3. Construction of the criteria partial scores

The z-score normalization method was used for each parameter in the study. This method allows for a comparison of the results across individuals and groups by transforming the raw data into a standardized score that reflects the distance from the mean in terms of standard deviation units. The z-score was computed for each participant based on the average value of the corresponding

TABLE 1 Baseline characteristics of individuals with progressive multiple sclerosis (pMS) and healthy subjects (HS).

Characteristics	pMS (n = 22)	HS (n = 19)*
Sex (M/F)	11/11	12/7
Age (years)	58 (14)	51 (17)
Height (m)	1.72 (0.08)	1.71 (0.06)
Weight (kg)	70.4 (15.3)	71.7 (14.3)
Body mass index (kg/m ²)	23.6 (4.1)	24.3 (4.3)
Concerning pMS		
Years since diagnosis	16 (10)	-
- Years since first sign	22 (15)	-
- Years since progression	11 (10)	-
Expanded Disease Status Scale	5.5 [3.5–6]	-
- Pyramidal function	3 [3–3]	-
- Cerebellar function	2 [0–3]	-
- Bulbar function	0 [0–1]	-
- Sensitive function	2 [0.5–2]	-
- Cognitive function	1 [0–2]	-
Multiple Sclerosis Walking Scale	65.72 (18.60)	-
Fatigue Impact Scale	42.74 (22.15)	-
Walking aid for the test (yes/no)	7/15	-
- Cane (1 or 2)	6	-
- Walker	1	-
- Human help	0	-
- Cane and human help	0	-

Mean (SD) or median [Q1–Q3] are given. *Data are missing for 2 HS subjects.

parameter in the reference group of HS in the same age range. A positive or negative z-score indicates that the value of the parameter for the participant is above or below the average value in the reference group, respectively. To facilitate interpretation, a z-coefficient of 1 or -1 was assigned to each parameter to indicate whether an increase in the parameter was considered beneficial or pathological, respectively. For gait criteria that included multiple parameters, the z-scores were merged with an arithmetic average to provide a single z-score for the criterion.

2.4. Clinical outcomes

The clinical outcomes assessed in pMS patients included both global severity outcomes, such as the Expanded Disability Status Scale (EDSS) and the Multiple Sclerosis Walking Scale-12 (MSWS), and functional severity scores, such as the Functional Scores (FS) obtained from the EDSS scale. Trained neurologists from Percy Hospital evaluated the FSs and total EDSS values before each trial. The MSWS was self-completed by the participants before each walking test visit.

TABLE 2 Reliability of parameters tested for inclusion in the semiogram.

Criteria	Parameter	Intra-session			Inter-session		
		ICC(1,1)	ICC(3,1)	SEM	ICC(1,1)	ICC(3,1)	SEM
Average speed	V (m/s)	0.97	0.97	0.01	0.96	0.96	0.01
Springiness	StrT (s)	0.98	0.98	0.01	0.93	0.93	0.02
	UtrT (s)	0.91	0.91	0.07	0.81	0.81	0.14
Smoothness	LDLJ-A (-)	0.91	0.91	0.02	0.82	0.82	0.04
	SPARC-G (-)	0.88	0.88	0.08	0.83	0.83	0.12
Steadiness	CVStrT (%)	0.78	0.78	0.12	0.82	0.82	0.15
	CVdstT (%)	0.49	0.49	0.15	0.64	0.64	0.21
	P1aCC (-)	0.94	0.94	0.01	0.90	0.90	0.01
	P2aCC (-)	0.88	0.88	0.01	0.87	0.87	0.01
Sturdiness	SteL (m)	0.96	0.96	0.00	0.95	0.95	0.01
Stability	RMS _{aML} (m/s ²)	0.95	0.95	0.01	0.90	0.90	0.02
Symmetry	iHR _{aAP} (%)	0.97	0.97	0.25	0.93	0.93	0.53
	iHR _{aML} (%)	0.95	0.95	0.22	0.86	0.86	0.46
	iHR _{aCC} (%)	0.97	0.97	0.20	0.90	0.90	0.59
	P1P2 _{aCC} (-)	0.56	0.56	0.01	0.53	0.53	0.02
	swT _r (-)	0.71	0.71	0.00	0.72	0.72	0.00
Synchronization	dstT (%)	0.96	0.96	0.19	0.94	0.94	0.38

Intraclass correlation coefficients [ICC(1,1) and ICC(3,1)] provide measures of relative reliability and standard error of the mean (SEM) values provide measures of absolute reliability.

2.5. Statistical analysis

2.5.1. Reliability

A test retest design was chosen to evaluate the variability of the measurement between intra-session and inter-session evaluations for both HS and pMS participants. Relative reliability was computed by using two models of the ICC, ICC(1,1) and ICC(3,1), which both assess the relative reliability of single measurements (41). ICC(1,1) is based on the hypothesis that all within-subject variability is due to measurement error and ICC(3,1) assumes that this variability is caused by systematic bias different from measurement error. Heteroskedasticity, a property of a variable that shows non-constant standard deviations across observations, could cause misinterpretation of the ICC (42). Thus, heteroskedasticity was ruled out by testing the Pearson correlation coefficient (r) between the absolute differences and the individual mean values against the null hypothesis. A low ICC can be due to within-subject variability or narrow ranges of values within the sample (22). To distinguish between these two explanations, the SEM was computed as a measure of absolute reliability.

2.5.2. Coherence

To ensure the relevance of each criterion, correlations between the parameters within each criterion and with other parameters were assessed. If there was a negative correlation between two

parameters within a criterion, the less informative parameter was excluded from the criterion.

2.5.3. Differences between groups

For each gait criterion and parameter, z-scores differences between groups were analyzed using the Mann-Whitney U -test.

2.5.4. Correlations with gait severity and functional status

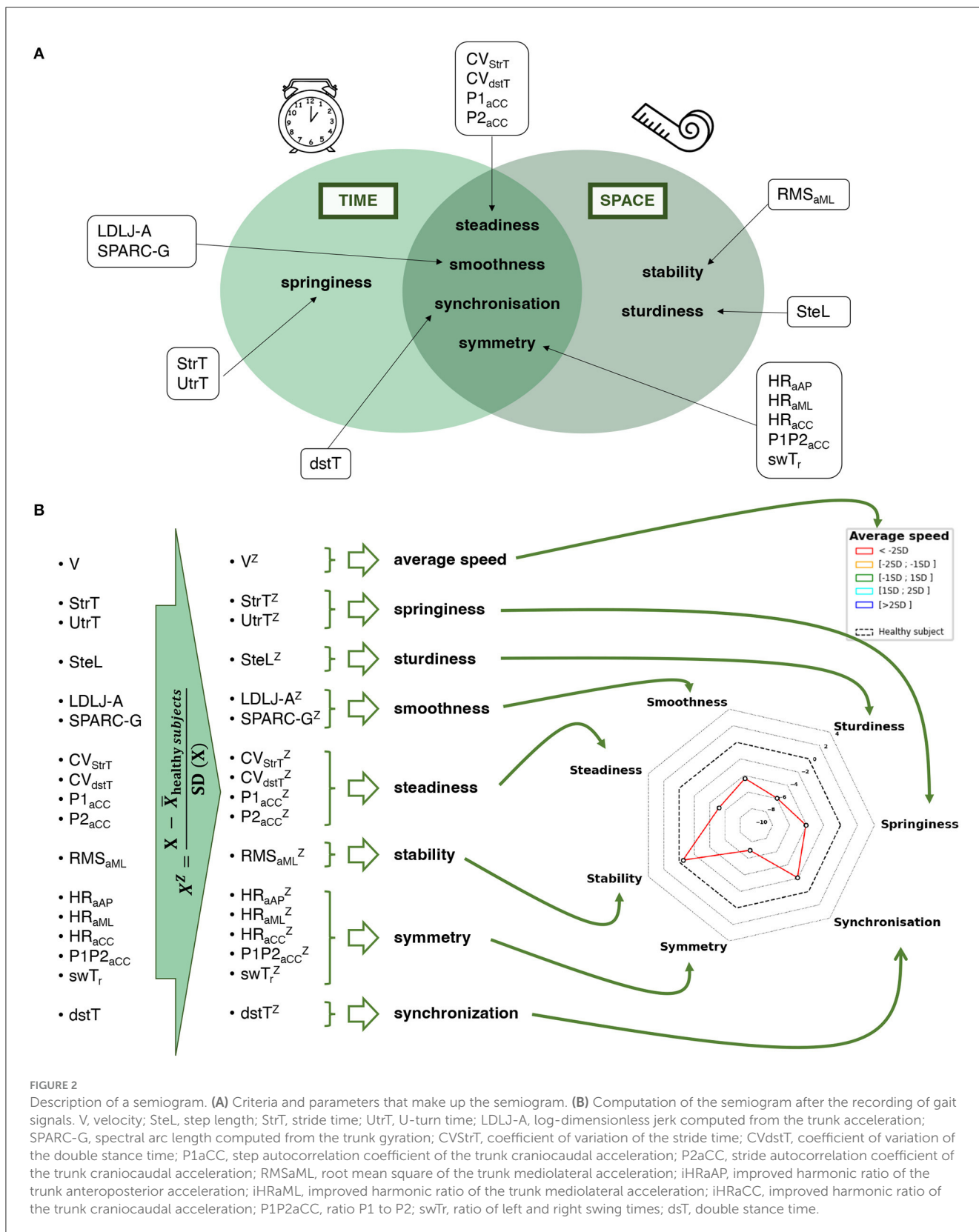
Correlation of z-scores with EDSS values and patient-reported outcomes as well as functional scores of the EDSS scale was assessed by the Pearson correlation coefficient and tested with the Fisher exact test.

Primary data analysis involved using MATLAB[®] R2020b and Python 3.8 and statistical analysis involved R v3.5.3. All analyses used two-sided tests, and $p \leq 0.05$ was considered statistically significant. Correction for multiple comparisons using Bonferroni adjustment was applied for all tests.

3. Results

3.1. Cohorts

Twenty individuals with pMS (10 females) and 19 age-matched HS (12 females) were enrolled in this longitudinal prospective study



(Table 1). The mean age was 58 (SD 14) and 54 (SD 9), respectively. In the pMS cohort, the median EDSS was high (5.5 [quartile 1 (Q1)-Q3: 3.5 6.0]) and seven patients needed a walking aid to perform

the test. Two participants from the HS cohort could not perform the measurement at 12 months. Therefore, only their first two visits were included. Four participants from the pMS cohort could not

perform the measurement at 18 months and only their first three visits were included. Thus, we had 110 trials from HS participants and 168 trials from pMS patients.

3.2. Construction and validity of the semiogram

3.2.1. Selection of reliable parameters

ICC(1,1) and ICC(3,1) values and SEMs are reported in [Table 2](#) for each of the 17 parameters considered for inclusion.

All parameters showed moderate to very high agreement (ICC ≥ 0.4) and were therefore included in the final score for the semiogram. Included parameters and corresponding criteria are illustrated in [Figure 2A](#).

3.2.2. Normative data from the reference group

For each of the 17 selected qualitative parameters, the mean and SD were computed for the reference group of 19 HS participants by using the whole set of trials (two trials for each participant at each visit, i.e., six trials per HS participant). The results are displayed in [Table 3](#).

3.2.3. Construction of the semiogram

The process for constructing the semiogram given the included parameters is outlined in [Figure 2B](#). All stages of the construction, from the signal to the final radar plot, are schematized in [Figure 3](#).

3.3. Validity of the semiogram

3.3.1. Intra-session test-retest of criteria scores for HS and pMS participants

Measures of intra-session relative reliability are plotted in [Figure 4](#), with distinct ICCs computed for HS and pMS participants. In the HS group, we observed excellent degrees of the intra-session agreement for speed and all qualitative criteria except steadiness and smoothness, which were moderate. A low SEM (steadiness: 0.06 z-score; smoothness: 0.05 z-score) indicates that the small range might be partly causing the low ICC. In the pMS group, speed and all qualitative criteria showed very high test-retest relative reliability, without exception. The detailed results for each parameter are provided in [Supplementary material 1](#).

3.3.2. Inter-session test-retest for HS and pMS participants

Measures of inter-session relative reliability between M0 and M6 were also computed for criteria ([Supplementary material 2](#)), with distinct ICCs computed for HS and pMS participants. In the HS group, ICCs were excellent or moderate, except one low but close to 0.4 for smoothness. All criteria showed very high reliability

TABLE 3 Mean, SD, and z-coefficient for included gait features for the reference group of 19 HS (six trials per participant, except for two participants without data at 12 months), for a total of 110 trials.

Criteria	Parameter	Mean	SD	Z-coefficient
Average speed	V (m/s)	1.22	0.20	+
Springiness	StrT (s)	1.10	0.09	-
	UtrT (s)	2.62	0.75	-
Smoothness	LDLJ-A (-)	-8.07	0.35	+
	SPARC-G (-)	-5.37	0.84	-
Steadiness	CVStrT (%)	2.34	0.97	-
	CVdstT (%)	5.63	2.07	-
	P1aCC (-)	0.82	0.10	+
	P2aCC (-)	0.82	0.10	+
Sturdiness	SteL (m)	0.68	0.08	+
Stability	RMS _{aML} (m/s ²)	1.28	0.33	-
Symmetry	iHR _{aAP} (%)	95.48	2.13	+
	iHR _{aCC} (%)	94.88	3.10	+
	iHR _{aML} (%)	86.77	6.32	+
	PIP2 _{aCC} (-)	0.96	0.04	+
	swT _r (-)	0.96	0.03	+
Synchronization	dstT (%)	23.34	3.50	-

For the z-coefficient, + and - respectively corresponds to 1 or -1, and indicate whether an increase in the parameter is considered beneficial or pathological.

for the pMS group. The detailed results for each parameter are provided in [Supplementary material 3](#).

3.3.3. Correlation between the parameters

Within each criterion, the correlations between parameters were always >0.3 . No parameters were excluded at this validation stage.

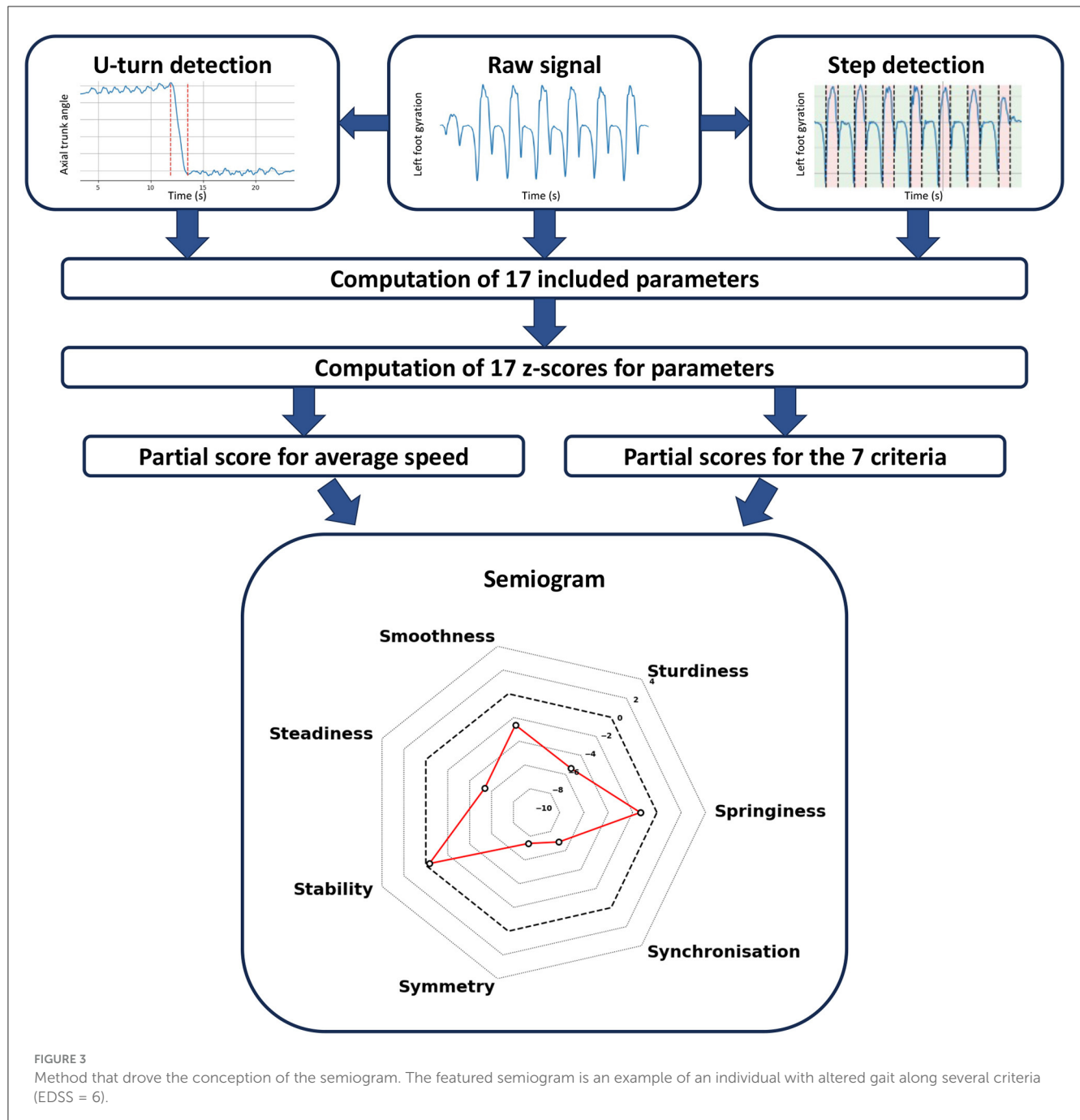
3.4. Difference between pMS and HS

When comparing pMS and HS participants, speed and all criteria but stability significantly differed ($p \leq 0.0001$). Results are displayed in [Figure 5](#). The detailed results for each parameter are provided in [Supplementary material 4](#).

3.5. Use for longitudinal follow-up of pMS

3.5.1. Correlation with disease global severity (EDSS, MSWS)

All the semiogram criteria were highly correlated to the validated general severity EDSS score. The subjective questionnaire score (MSWS) was moderately correlated with speed, springiness, smoothness, and steadiness, and was independent of the four other criteria ([Table 4](#)).



Examples of a semiogram for an individual with severe disease (EDSS 6.0) and less severe disease (EDSS 3.5) and an HS are given in Figure 6.

3.5.2. A window into the functional status of the disease: correlation with functional status scores

All criteria were moderately to strongly associated with the Pyramidal FS (positive association for stability and negative for the others; Table 5). Cerebellar alterations were also positively correlated with stability and negatively correlated

with all other criteria except symmetry. Sensitive lesions were associated with altered symmetry and improved stability. The bulbar sub-score was associated with altered speed, synchronization, and sturdiness. The cognitive sub-score was associated with altered speed, smoothness, steadiness, and sturdiness.

3.5.3. An example of longitudinal follow-up

The longitudinal follow-up over an 18-month period is illustrated in Figure 7 for an individual with a high disability. The

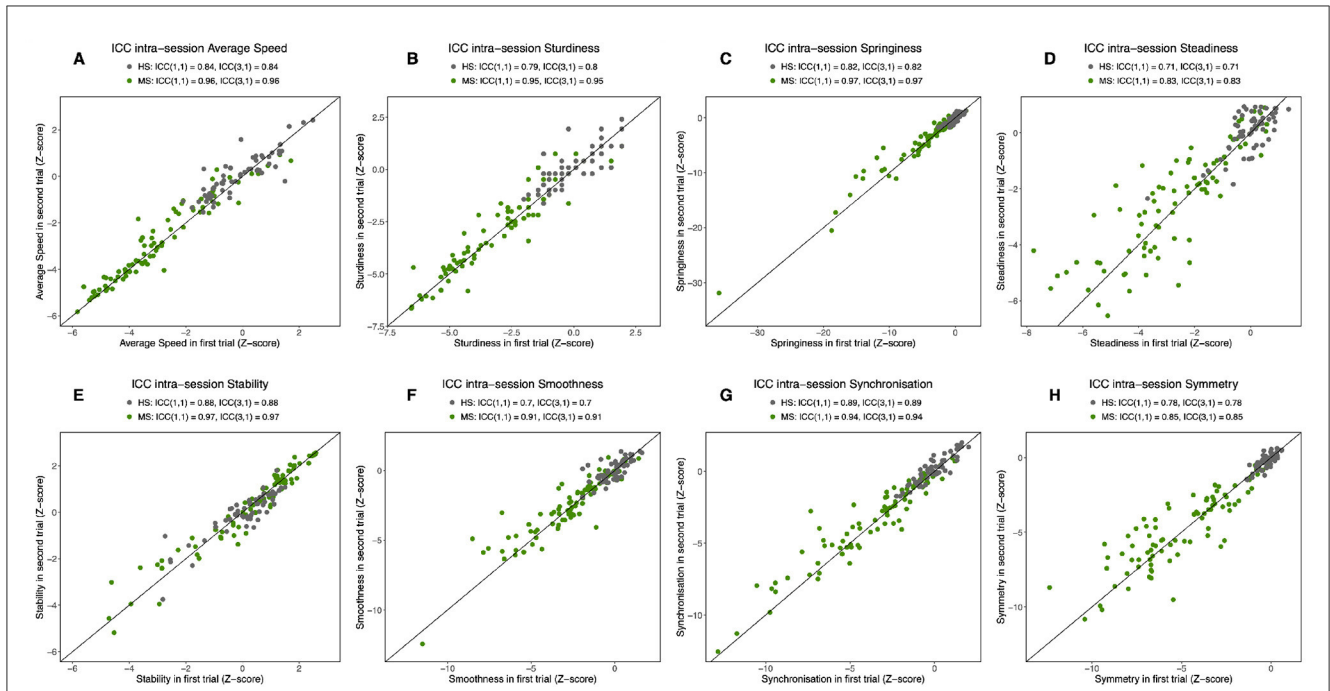


FIGURE 4 Intra-session intraclass correlation coefficients (ICCs). For speed (A) and the seven criteria for the semiogram: sturdiness (B), springiness (C), steadiness (D), stability (E), smoothness (F), synchronization (G), and symmetry (H). ICCs are reported for the two populations separately: progressive multiple sclerosis (pMS) and healthy subjects (HS). ICC(1,1) supposes that subject variability is due to measurement error.

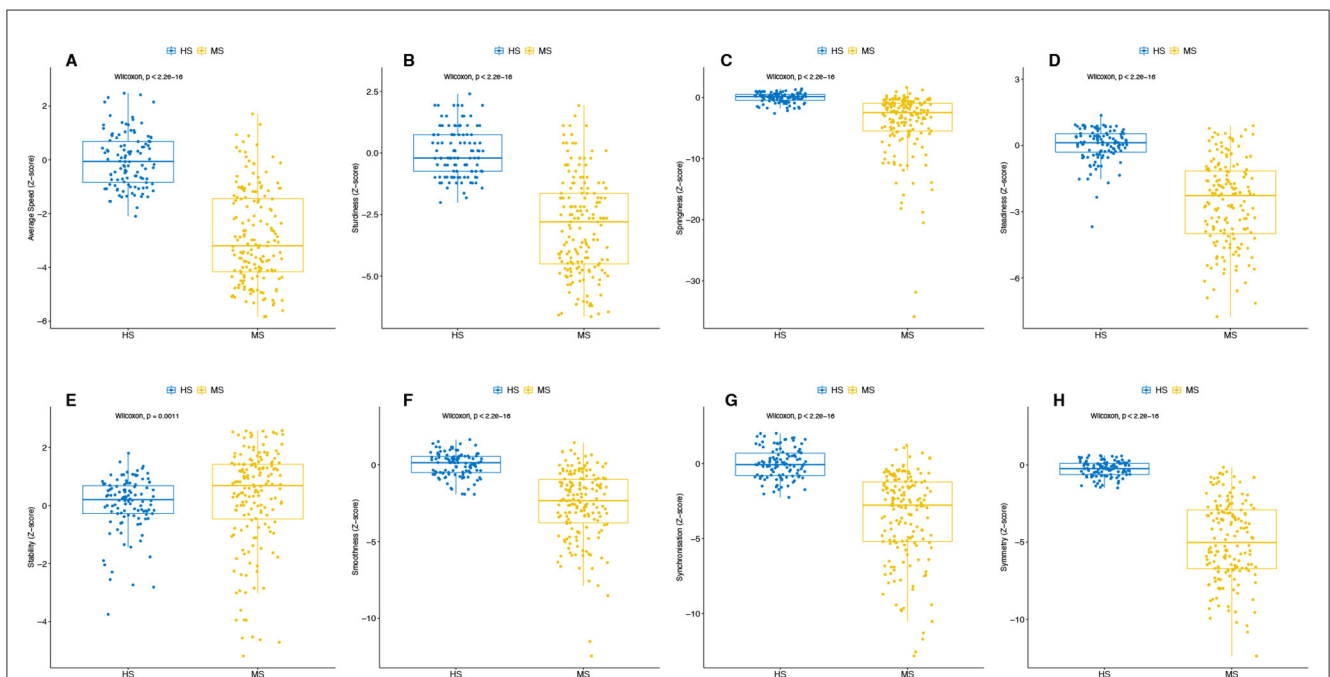


FIGURE 5 Difference in speed and each criterion of the semiogram between the two populations (HS and pMS). For speed (A) and the seven criteria for the semiogram: sturdiness (B), springiness (C), steadiness (D), stability (E), smoothness (F), synchronization (G), and symmetry (H). All tests of the participants are included in the analysis. The p -value from the Wilcoxon test is reported.

EDSS at inclusion was 6.0 and remained at that level at month 6. It then increased to 6.5 at month 12. At month 18, the EDSS was again 6.5. A qualitative analysis of semiograms at different times shows

that the individual displayed higher differences than the norm at months 12 and 18 (Figures 7C, D) as compared with months 0 and 6 (Figures 7A, B).

4. Discussion

In the present study, we introduce the semiogram, a novel multidimensional approach for automated assessment and visualization of gait in routine neurological practice. The main objective of this concentric sector chart is to allow physicians

to quantitatively assess the semiological characteristics of their patients' gait in relation to the general population and to track the evolution of each criterion throughout the pathology. Each branch of the chart represents a semiological criterion of the patient's gait, such as springiness, smoothness, steadiness, sturdiness, stability, symmetry, or synchronization. Average speed, which is recognized in the literature as a global gait parameter (7), influences the resulting color of the chart.

TABLE 4 Correlation coefficients for the semiogram criteria with the EDSS and MSWS scores.

	MSWS		EDSS	
	r	p-value	r	p-value
Speed	-0.18	0.024	-0.74	≤0.001
Springiness	-0.20	0.012	-0.50	≤0.001
Smoothness	-0.24	0.003	-0.63	≤0.001
Steadiness	-0.18	0.026	-0.59	≤0.001
Sturdiness	-0.15	0.062	-0.70	≤0.001
Stability	0.00	0.987	0.33	≤0.001
Symmetry	0.03	0.727	-0.44	≤0.001
Synchro	-0.05	0.543	-0.63	≤0.001

Significant correlations appear in bold type.

The semiogram is suitable for clinical practice. It is based on the use of three easily deployable IMUs in a short-distance test and does not require any specific space or platform. Even if using a short walking test may reduce the robustness of some parameters, they are commonly used in clinical practice as they are more practical and easier to conduct (7), particularly for individuals with severe pMS who may find longer walking tests difficult to complete. It has also been found that uninterrupted walking for more than 2 min is not common in real-life situations (43). Moreover, a correlation exists between the gait assessed in the laboratory and the daily ambulation (17). Most parameters of the semiogram require a walking event segmentation algorithm. To obtain a tool deployable in routine clinical practice, this segmentation should be automated without manual review, which remains a challenge in gait quantification. Detecting highly degraded steps, such as those in our cohort, is often difficult with conventional

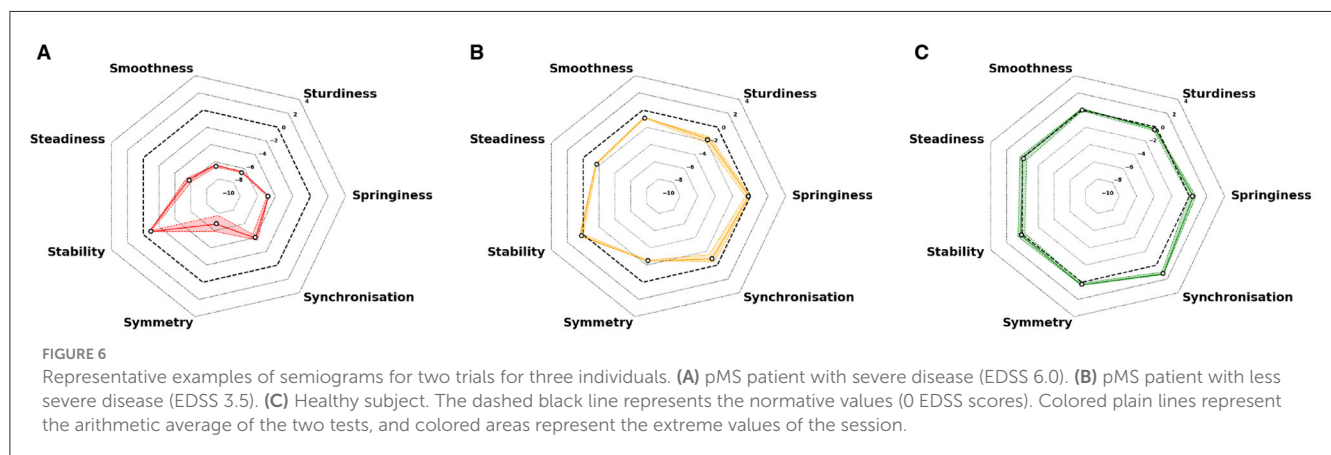
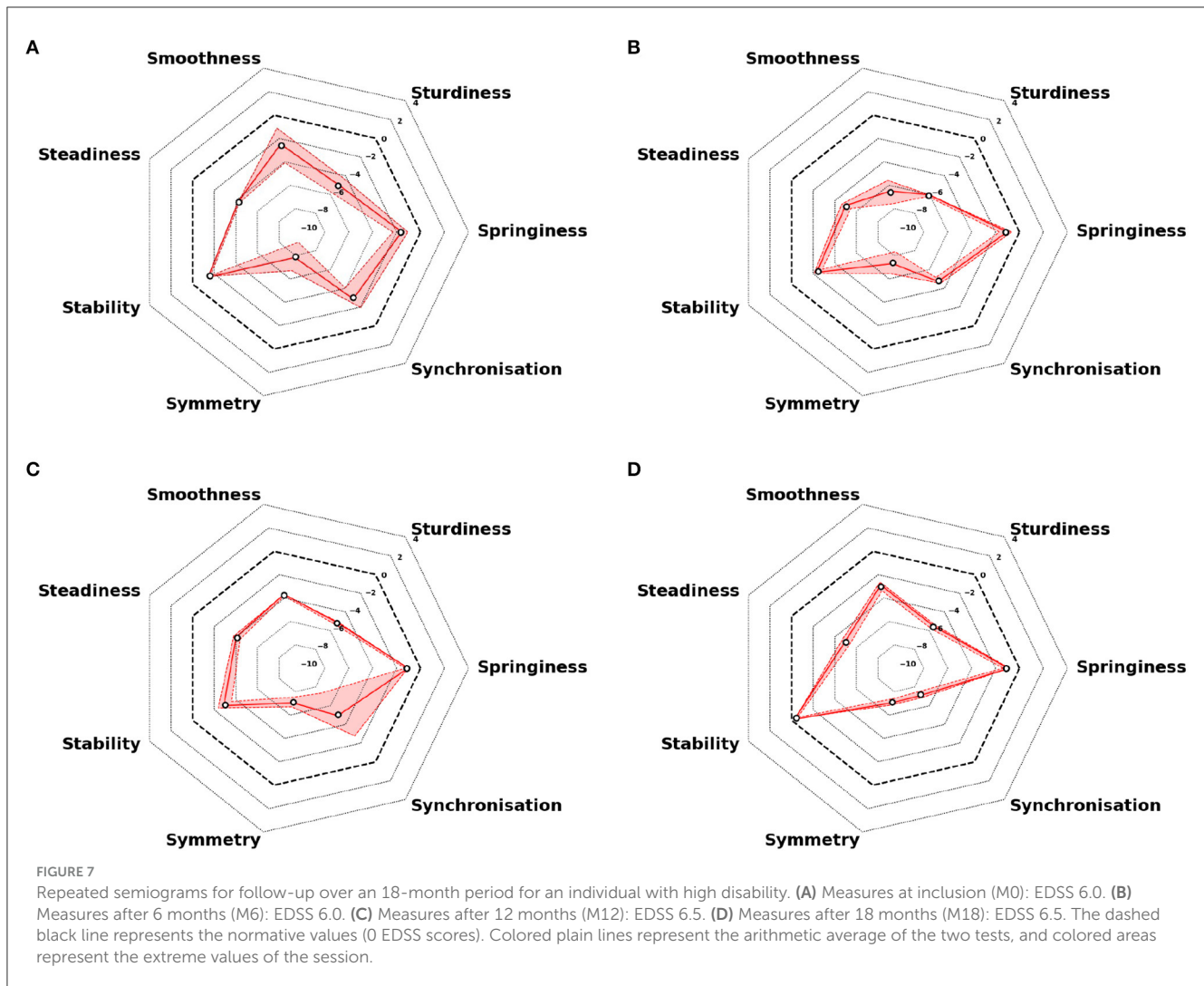


TABLE 5 Correlation coefficients for the semiogram criteria with the functional sub-scores.

	EDSS									
	Pyramidal		Cerebellar		Sensitive		Bulbar		Cognitive	
	r	p-value	r	p-value	r	p-value	r	p-value	r	p-value
Speed	-0.64	≤0.001	-0.52	≤0.001	-0.11	0.182	-0.24	0.006	-0.33	≤0.001
Springiness	-0.52	≤0.001	-0.16	0.068	-0.10	0.241	-0.09	0.307	-0.10	0.229
Smoothness	-0.52	≤0.001	-0.33	0.001	-0.05	0.597	-0.09	0.312	-0.18	0.038
Steadiness	-0.39	≤0.001	-0.37	≤0.001	0.10	0.233	-0.07	0.451	-0.40	≤0.001
Sturdiness	-0.56	≤0.001	-0.53	≤0.001	-0.04	0.657	-0.23	0.007	-0.41	≤0.001
Stability	0.44	≤0.001	0.34	≤0.001	0.31	≤0.001	0.13	0.139	-0.01	0.907
Symmetry	-0.24	0.004	-0.04	0.670	0.23	0.005	-0.08	0.363	-0.05	0.589
Synchro	-0.64	≤0.001	-0.27	0.001	-0.13	0.136	-0.21	0.015	0.01	0.914

Significant correlations appear in bold type.



algorithms and requires a previously validated algorithm (27). Finally, the visual interpretation of the semiogram and the ability to overlay examinations from multiple months apart provide valuable assistance to clinicians in the quantitative analysis of gait data.

The semiogram is a reproducible tool, consistent with the semiological and clinical descriptions of gait in the literature. Indeed, the originality of our study lies in the selection of potential parameters based on a systematic literature review and their clinical application in patients with pMS (7), which enhances the external validity of our approach. Even if the initial literature review only included 78 studies due to quality selection issues (7), we updated it with a permanent bibliographic survey. We then included the parameters more recently appeared, in particular in the case of smoothness for which there was a consequent number of publications (29). For both HS and pMS cohorts, the intra-session test-retest agreement is moderate to very high for all included parameters and criteria (Table 2), which demonstrates the reproducibility of the measurements under the conditions of the 10-m walking test. Inter-session test-retest agreement is also moderate to very high comparing M0 and M6 (Table 2), thus validating the use of the semiogram for bi-annual visits, which

is a frequent practice in neurological care. Previous research has also investigated other multidimensional gait scores in a free-living environment (44, 45) or in a clinical environment, such as the study of Mansour et al., who developed a multifeatured gait score and evaluated it in an older population (40). Several differences from this score enhance the relevance of our multidimensional score. In our study, the gait criteria are based on clinical standards (46) and therefore follow closely the clinical evaluation currently done in routine practice. Unlike the multi-feature gait score proposed by Mansour et al., we evaluate the reliability of each parameter separately before inclusion and do not eliminate redundancy in our semiogram. Beyond the difference in method regarding the selection of parameters and their categorization into different criteria, it is important to note that the internal validity, assessed through the reproducibility of measurements, is similar in both studies, based on similar walking tests.

The semiogram is clinically relevant. On a macroscopic level, it differentiates indeed pathological participants from healthy subjects. The evaluation of parameters and criteria consistently shows a significant distinction between the two cohorts in all instances, except for stability. Specifically, pMS individuals

exhibited shorter steps (lower sturdiness), lower cadence and higher U-turn time (lower springiness), higher variability (lower steadiness), higher perturbations within their walk (lower smoothness), higher double stance time (lower synchronization between right and left cycle), and more asymmetrical behavior (lower symmetry) than HS individuals. At a more granular level, the semiogram offers valuable insights into disease severity and functional status of patients. In terms of disease global severity scores, the objective EDSS test exhibits a highly significant negative correlation with all criteria of the semiogram, except for stability. This finding aligns with the majority of studies and meta-analyses that have explored parameters such as velocity, step length, and average step duration, which are widely investigated in the field (16, 47, 48). These observations are also in line with the results obtained with more global approaches used to analyze the signal obtained with IMUs (49). Other parameters that necessitate precise segmentation of walking events have received less attention in research. Concerning stability, it is observed to increase with disease severity. This phenomenon has been previously attributed to decreased walking speed in severe diseases, an increase of double stance time, and a reduction in swing phase amplitude (50). In our study, only one parameter is used for stability assessment, the mediolateral root mean square. Recent studies have described other parameters that accurately reflect stability in neurological pathologies, such as the local divergence exponent (51). This parameter could be investigated to confirm if the trend holds true. According to the existing literature, the MSWS, which provides a subjective assessment of the patient's disease activity, seems to exhibit a weaker correlation with gait deterioration than EDSS (16). However, some studies emphasize that because being based on the patient's perception, the MSWS test may actually be more effective than objective scores in detecting significant gait deterioration (52). However, due to the limited sample size, we are unable to examine whether the semiogram can effectively monitor changes over time. The statistical power is insufficient, as only four out of 22 participants with pMS experienced a 1-point or greater change in their EDSS status during the follow-up period. To overcome this limitation, future studies should involve a larger sample size and a longer follow-up duration to provide more robust findings. Regarding functional status, the results confirm that pyramidal and cerebellar disorders are the primary contributors to gait degradation in the pMS cohort (11). Furthermore, various gait features have been identified as capable of distinguishing between individuals with pMS who exhibit predominant pyramidal dysfunctions and those with predominant cerebellar dysfunctions. For instance, individuals with pyramidal dysfunctions demonstrated significantly lower cadence, longer double stance time, and more asymmetrical gait compared to those with cerebellar dysfunctions (53). The semiogram enables the decomposition of gait analysis and facilitates the identification of associations between criteria and functional impairments. Our study revealed that reduced springiness and symmetry were specifically associated with pyramidal dysfunction rather than cerebellar tract disorders, which aligns with previous research findings (11). These findings highlight the importance of considering the specific type of dysfunction when assessing gait in pMS patients.

Another advantage of the semiogram relies on its capacity to integrate multiple validated parameters, enabling a comprehensive and sensitive analysis of gait. This approach ensures that each criterion is captured as accurately as possible. In our study, the construction of the semiogram is based on parameters commonly utilized in neurological disorders, rather than being specific to pMS (29, 30, 34, 54). Therefore, the applicability of this method can be readily extended to other neurological disorders by conducting a subsequent literature search. This approach eliminates the limitations associated with relying solely on a single parameter and allows for a more comprehensive assessment of gait across various neurological conditions (55). Another concern is the resolution of the semiogram. We have used one standard deviation (SD). However, it should be noted that the z-scores of the various parameters represented can be decimal numbers. Furthermore, Bohannon et al. have indicated that even small changes in gait parameters can have clinical significance (56). Interpretation of the semiogram and its correlation with the clinic is therefore variable, and depends in particular on the alteration in gait and the pathology being studied. It can therefore only be conceived in conjunction with the examination of the patient, and the resolution could be adapted to different patient cohorts. Indeed, further validation in other patient cohorts such as those with Parkinson's disease, Alzheimer's disease, cerebellar ataxia, and stroke, as reviewed by Vienne et al. (7), would be valuable. By applying the semiogram method to these different neurological conditions, we may assess its effectiveness and generalizability, expanding its utility beyond the specific context of progressive multiple sclerosis.

5. Conclusion

The wearable technology discussed in this study offers an innovative way to collect and visualize objective and quantitative data on mobility that was not previously available in a clinical setting. This technology has the potential to serve as an important outcome measure for evaluating mobility impairment in individuals with pMS. Furthermore, the use of evidence-based criteria and the semiogram visualization provides a quick and comprehensive assessment of gait that can be incorporated into clinical practice. The radar plot visualization may also aid both patients and clinicians in tracking disease progression over time.

Data availability statement

The healthy subjects dataset and the online demonstration of the semiogram are accessible at the following address: <https://www.ipol.im/>.

Ethics statement

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.

Author contributions

CV and NE conceived the study, participated in the analysis, and wrote the manuscript. AV-J, AM, and FQ conceived the study and participated in the data acquisition. FB, MS, M-LB, IT, CT, and ED participated in the data acquisition. DR conceived the study, participated in the data acquisition, and edited the manuscript. LO conceived the study and edited the manuscript. All authors contributed to the refinement of the study protocol and approved the final manuscript.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary Material for this article can be found online at: <https://www.frontiersin.org/articles/10.3389/fneur.2023.1237162/full#supplementary-material>

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3.3 Application à l'évaluation post opératoire du PVES

Le semiogramme ayant montré une pertinence clinique dans le suivi longitudinal des patients souffrant de SEP, nous avons voulu l'appliquer à notre cohorte de patient souffrant de PVES post AVC chez qui le traitement chirurgical était indiqué pour le suivi du résultat de l'intervention chirurgicale. L'approche est différente de ce qui a été réalisé chez des patients atteints de SEP puisqu'elle a consisté en la comparaison de deux examens pré et post opératoire. Nous avons voulu évaluer la sensibilité et la spécificité du semiogramme comparativement à un score fonctionnel simple et le plus utilisé dans ce contexte, la GAS. L'objectif est d'évaluer la variation de l'aire relative du semiogramme au regard de l'évolution fonctionnelle, en recherchant une augmentation de l'aire du semiogramme en cas d'amélioration et inversement en cas de dégradation ou d'absence d'effet (Figure 10). Cette chirurgie ayant une action centrée sur le pied chez des patients atteints d'hémiplégie pour lesquels le handicap à la marche peut avoir de multiples étiologies, le semiogramme devrait permettre d'en évaluer l'effet sur la marche globale, sans pour autant s'attendre à un retour à la normale.

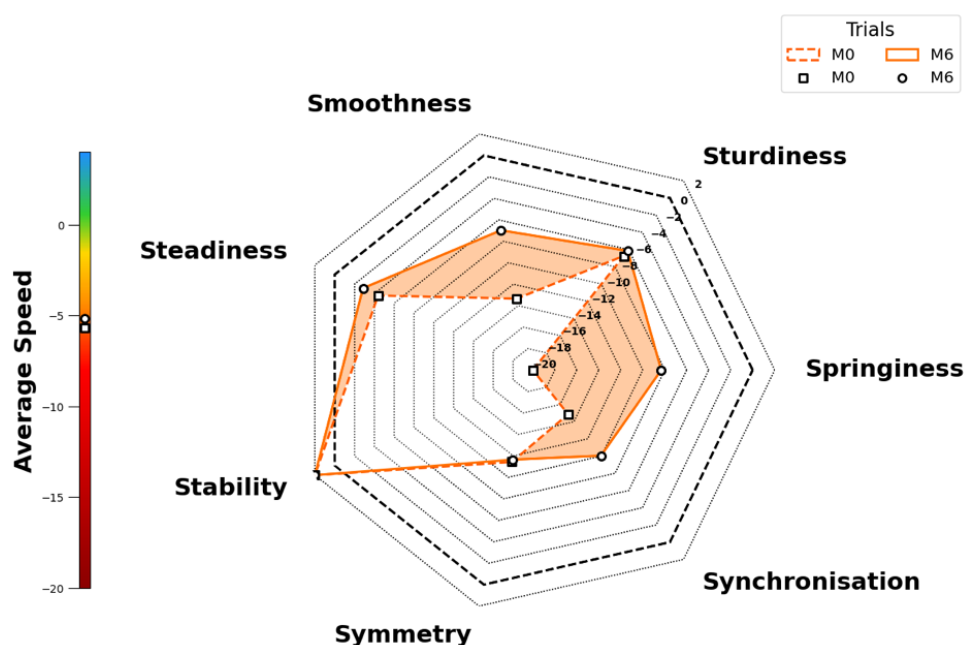


Figure 10 : Variation de l'aire du semiogramme témoignant d'une amélioration de la marche entre deux examens successifs à M0 et M6.

Inertial Measurement Units to evaluate the efficacy of Equino Varus Foot surgery in post stroke hemiparetic patients

Nicolas de l'Escalopier

HIA Percy

Cyril Voisard

Université Paris Cité, Université Paris Saclay, ENS Paris Saclay, CNRS, SSA, INSERM, Centre Borelli

Sylvain Jung

Université Paris Saclay, Université Paris Cité, ENS Paris Saclay, CNRS, SSA, INSERM, Centre Borelli

Mona Michaud

Université Paris Cité, Université Paris Saclay, ENS Paris Saclay, CNRS, SSA, INSERM, Centre Borelli

Albane Moreau

Université Paris Cité, Université Paris Saclay, ENS Paris Saclay, CNRS, SSA, INSERM, Centre Borelli

Nicolas Vayatis

Université Paris Saclay, Université Paris Cité, ENS Paris Saclay, CNRS, SSA, INSERM, Centre Borelli

Philippe Denormandie

Raymond Poincaré University Hospital

Alix Verrando

HIA Percy

Claire Verdaguer

HIA Percy

Alain Moussu

HIA Percy

Aliénor Jequier

HIA Percy

Christophe Duret

CRF Les Trois Soleils

Laurence Mailhan

Institution Nationale des Invalides

Laure Gatin

Raymond Poincaré University Hospital

Laurent Oudre

Université Paris Saclay, Université Paris Cité, ENS Paris Saclay, CNRS, SSA, INSERM, Centre Borelli

Damien Ricard (✉ damien.ricard@m4x.org)



Université Paris Cité, Université Paris Saclay, ENS Paris Saclay, CNRS, SSA, INSERM, Centre Borelli

Research Article

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Abstract

Introduction

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

Methods

Patients with post-stroke equinovarus foot, 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 Scale 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 and 50% (10/20) had an improvement in walking technique as evidenced by the cessation of the use of a walking aid. Considering the semiogram, the measurement of the area weighted by average speed demonstrated very good reproducibility ($ICC(1, 3) = 0.80$). In the group with a positive functional outcome (GAS T score ≥ 50), the change in the area 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 (two patients) with unfavorable results, the area under the curve changed by + 2.3%, -10.2% and - 9.5%.

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.

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 [2]. The preoperative evaluation is delicate and relies on consultation between the different actors of the management [3, 4]. Neuro orthopaedic surgery for SEVF encompasses a combination of tendon and nerve procedures performed by a single team [5, 6]. It provides a satisfactory functional result in most cases, even if precise assessment remains difficult and complex to reproduce [7].

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 [7]. For this reason the evaluation of the result is therefore mainly based today on a subjective functional evaluation, with the Goal Attainment Scale appearing as the most reliable tool [8–10]. 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 [11]. 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 [12].

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 [13]. 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 [14–17]. In post stroke patients, several parameters have shown good reliability [18–20]. However, IMUs have never been used in post-operative evaluation in this population. The semiogram is an innovative tool based on IMUs including several mathematical and physical parameters divided into seven clinical characteristics, allowing a visual feedback on gait evaluation and evolution through a radar diagram [21, 22]. It offers an instantaneous analysis of gait, which clinicians can conveniently interpret. By combining relevant parameters found in the literature [23, 24], 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.

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 [7]. 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 efficacy of Equino Varus Foot surgery in post stroke hemiparetic patients, and his comparison with functional analysis obtained by GAS.

Surgical procedure

Surgical management was decided during a multidisciplinary neuro-orthopaedic consultation. It was comprehensive, incorporating both tendon and nerve procedures, and aligned with the current state of the art [3, 5, 6]. 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 sec, walking 10 m at comfortable speed, U-turn, walking 10 m at comfortable speed, standing position for 5 sec. 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 [8, 9], 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, 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:

$$T = 50 + \frac{10 \sum W_i X_i}{\sqrt{[(1 - \rho) \sum W_i^2 + \rho (\sum W_i^2)]}}$$

where:

- X_i = GAS score
- W_i = weight of each GAS scale (2/1)
- $\rho = 0.3$ correlation coefficient between GAS scores [25, 26].

We also used a binary GAS which separates good functional results ($GAS \geq 0$) 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 [22], applicated with an automated gait events segmentation algorithm [21]. The calculation methods for each parameter were derived from the literature and are detailed in a previous paper [22]. 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 [19, 24, 27–30]
3. Steadiness: refers to gait regularity.
4. Sturdiness: refers to gait amplitude.
5. Stability: refers to gait balance [31].
6. Symmetry: refers to right/left concordance during gait [32–35].
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:

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

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.

Table 1
Patients characteristics and type of surgery.

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

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 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

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 with a F1-score of 96.3%, with a recall of 96.7% and a precision of 96.0% compared to GaitRite [21]. 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.

About ordinal statistical correlation tests, we did not observe any trends favoring one criterion over the others in reflecting GAS results (results not provided in the article). 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. The results of these tests are not included in the article, except for average speed, which is a parameter often studied. 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 \geq 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 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, 5, 36, 37]. As reported by Salga et al. [3] we believe that that this specific approach should be carried out by specialized teams performing the full range of available procedures, rather than by separate neurosurgical or orthopedic teams [2, 6, 38].

Evaluation methods in SEVF surgery

As previously shown in a literature review [7], the impact on patients' overall gait is very difficult to quantify clinically, 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 [5, 9, 39, 40]. 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 [9]. 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 [16, 22].

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 [41], 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 [13, 18, 19, 42, 43]. 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. [44–46]. 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 [47]. All algorithms can be

accessed and used online at <https://www.ipol.im/>. The use of 7 different clinical 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 [22]. 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 [11]. 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 polygons 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 [48], or an innovative surgical procedure [11]. 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 [49, 50] or toxin for which semiogram could be of real interest in individual longitudinal monitoring [51].

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. Combined with a functional scale such as the GAS, they can provide a global analysis of the effect of surgery.

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.

Availability of data and materials

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

Competing interests

The authors declare that they have no competing interests.

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No funding was received to conduct this research

Authors' 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.

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Figures

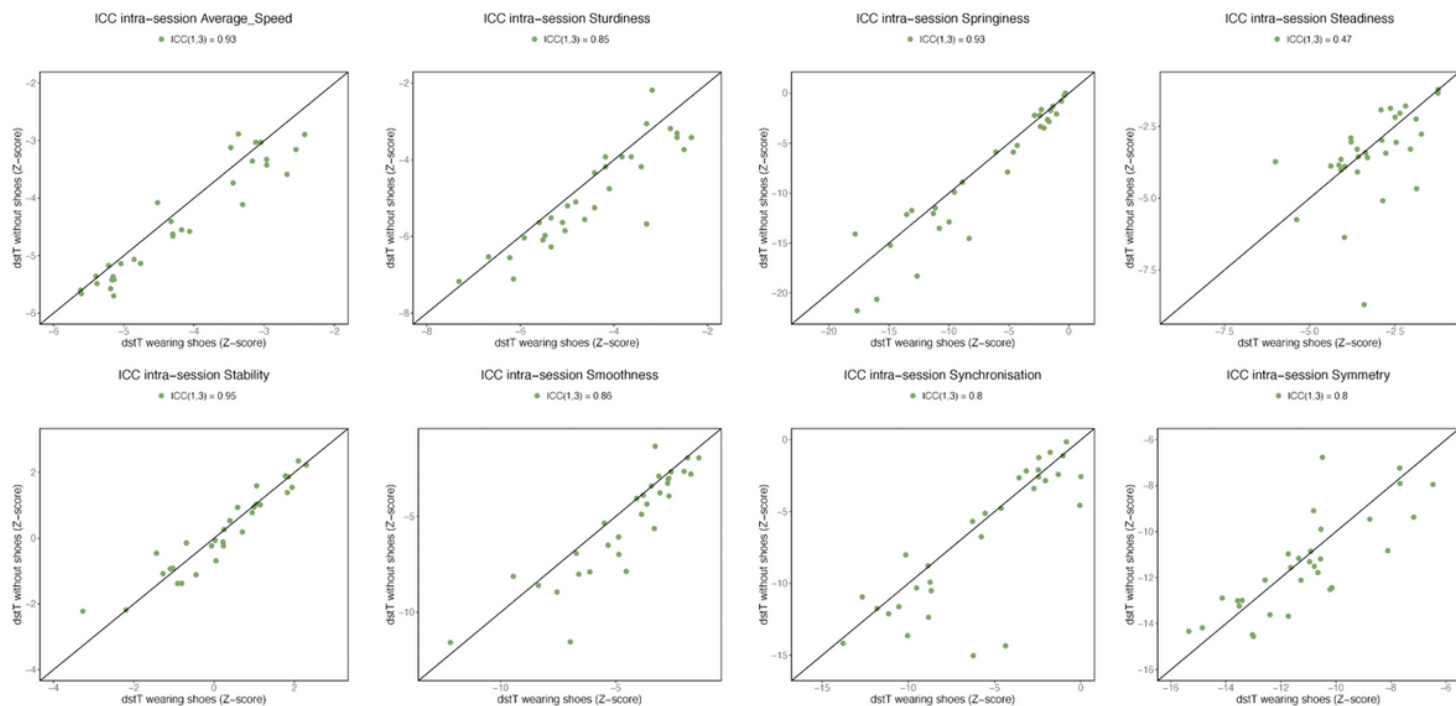


Figure 1

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.

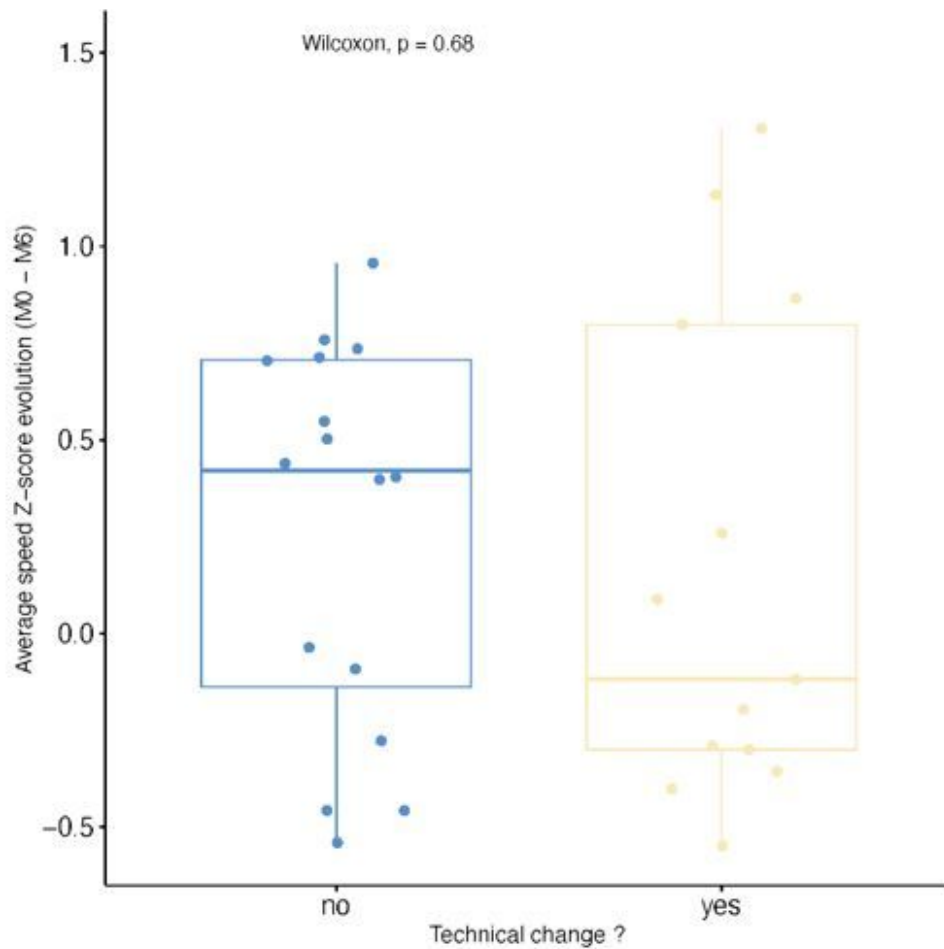


Figure 2

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

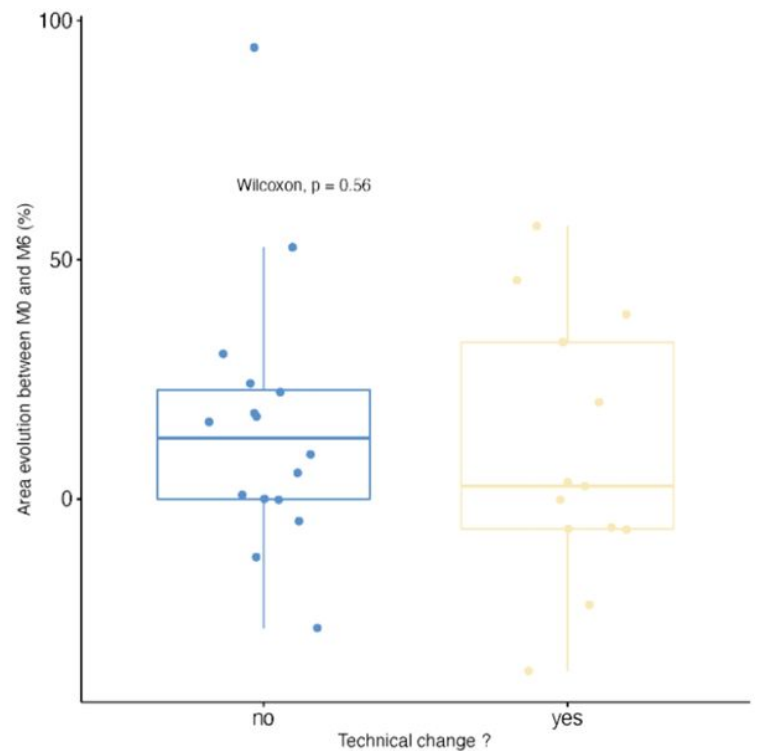
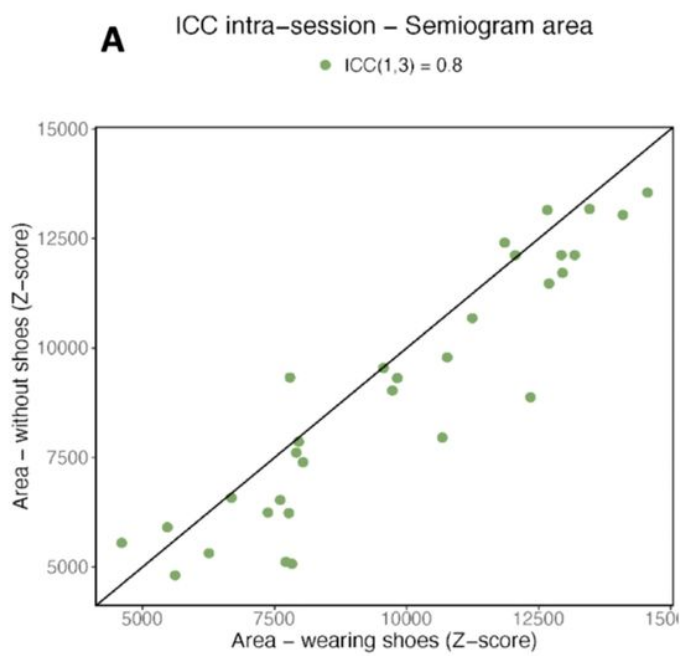


Figure 3

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.

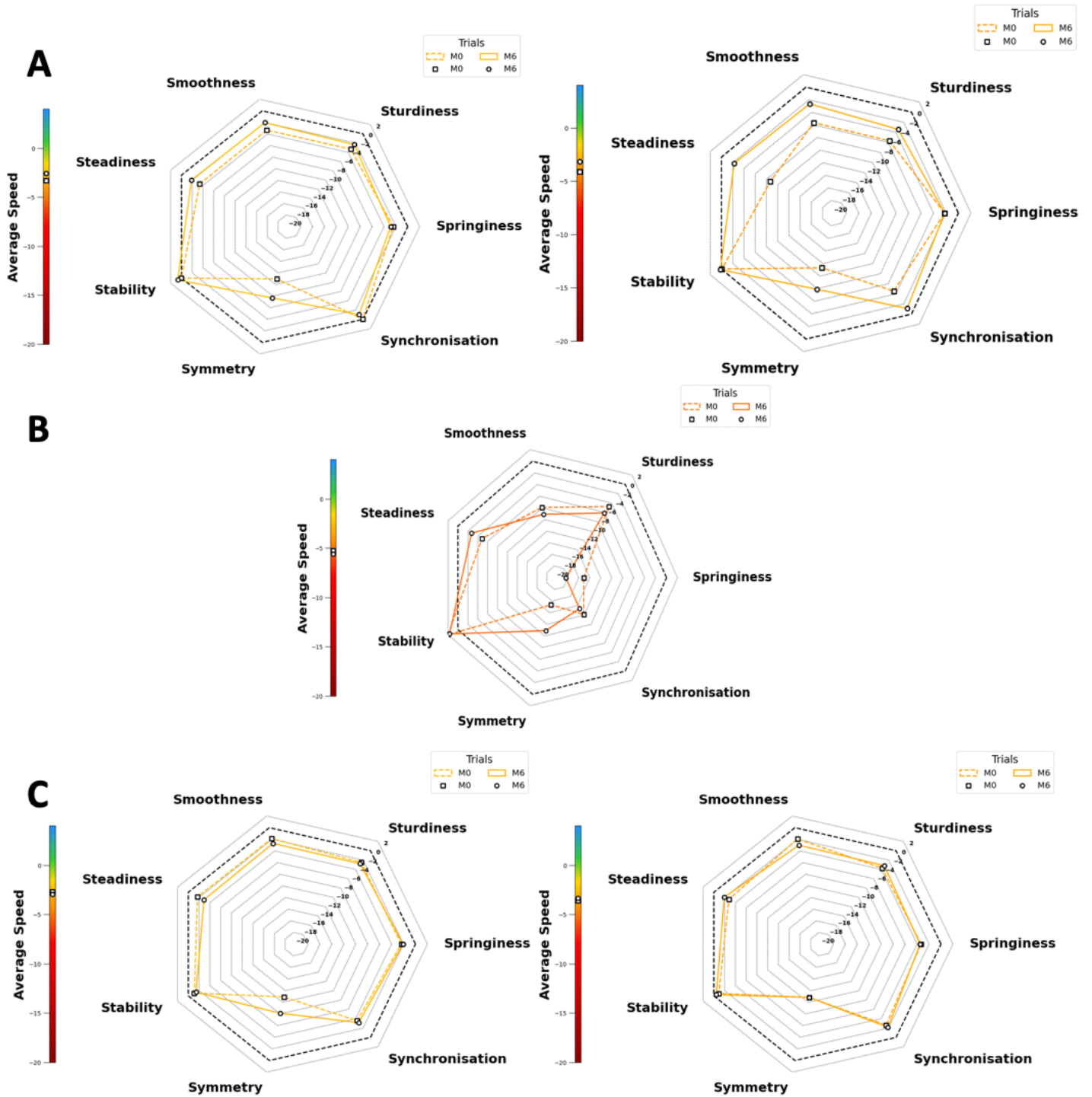


Figure 4

- 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 significant 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).

4. Discussion

4.1 Stratégie chirurgicale neuro-orthopédique

Il existe une grande hétérogénéité des attitudes selon les équipes, réparties entre les gestes neurologiques et tendineux. Depuis plusieurs années, la réalisation de l'ensemble de ces gestes par les mêmes équipes a permis d'affiner les indications et de réaliser des gestes combinés (Allart et al., 2021; Deltombe et al., 2018; Genêt et al., 2019; Salga et al., 2022). Les résultats fonctionnels de notre série sont en accord avec les séries récentes utilisant la même approche (Deltombe et al., 2018). Ils montrent une efficacité importante de cette prise en charge, permettant une amélioration significative de la marche et l'arrêt de l'utilisation d'aides techniques comme les chaussures orthopédiques ou les orthèses.

4.2 Évaluation post opératoire actuelle

4.2.1 Évaluation fonctionnelle

Si l'approche chirurgicale tend à se normaliser, cela n'est pas le cas concernant l'évaluation post opératoire des patients. Au niveau fonctionnel, de nombreuses échelles et méthodes de mesure ont été utilisées, mais aucune ne s'est imposée. Ceci montre clairement l'absence d'une échelle générique validée pour l'évaluation de la marche chez les patients hémiparétiques (de l'Escalopier et al., 2022; Renzenbrink et al., 2012). L'échelle permettant une analyse la plus spécifique possible centrée sur le patient et qui est aujourd'hui la plus utilisée est la GAS (Krasny-Pacini et al., 2013). Cependant elle garde des limites importantes notamment lorsqu'elle est utilisée par des équipes non expérimentées.

4.2.2 Évaluation instrumentale

Notre étude a montré les limites de l'état de l'art actuel pour l'utilisation de l'analyse instrumentale de la marche dans cette indication. Si elle a un intérêt démontré dans la

planification préopératoire des interventions, elle n'est que très rarement utilisée en post opératoire et de façon très hétérogène. Sa combinaison avec une évaluation fonctionnelle est aussi très limitée. Cette comparaison pré et postopératoire de l'analyse de la marche semble essentielle pour évaluer l'effet du geste. La comparaison de la cinématique articulaire pré et postopératoire est un critère fiable et reproductible qui peut être mesuré par analyse instrumentale (Carda et al., 2009). Les méthodes instrumentales d'analyse de la marche sont d'une aide considérable. L'AQM offre une analyse plus fine des résultats chirurgicaux, et permet d'améliorer la pertinence de la stratégie chirurgicale dans le PVES conduisant à définir des stratégies plus standardisées (Fuller et al., 2002). Cependant si l'AQM peut apporter de précieux éléments aux équipes spécialisées, elle reste difficile à généraliser. En effet aucun indicateur validé et reproductible de la marche n'a été utilisé. Par exemple, seules trois études ont évalué la symétrie du pas, et les trois indicateurs étaient différents (Le Bocq et al., 2016; Nonnekes et al., 2019; Patterson et al., 2008). La plupart des études n'ont utilisé l'analyse instrumentale que pour recueillir des données spatiotemporelles simples ou des données sur la cinématique des articulations, ce qui représente une contribution limitée. Aucune équipe n'a recueilli les données brutes des signaux pour les analyser.

4.3 InertialoLocographie

L'ILG consiste à utiliser les données accélérométriques et gyroscopiques combinées d'une unité de mesure inertielle. Les IMUs ont l'avantage d'être légers, peu coûteux et faciles à utiliser dans la pratique. Cette approche a été validée pour une utilisation clinique dans l'évaluation de la marche chez les patients souffrant d'arthrose ou de pathologies neurologiques, telles que l'hémiplégie post-AVC (Barrois et al., 2016, 2015; Mizuike et al., 2009; Vienne et al., 2017; Yang et al., 2013). Un autre avantage est la possibilité d'effectuer des mesures ambulatoires sur une période plus longue dans l'environnement du patient (Jung et al., 2020), ce qui n'est pas réalisable avec l'AQM. D'autre part, la comparaison avec les normes de sujets sains est un critère peu utilisé mais qui semble corrélé à l'amélioration de la marche. Cette étude transversale de la marche représente un élément complémentaire dans l'évaluation de l'amélioration postopératoire (Pinzur et al., 1986). Cela peut être possible avec l'ILG en utilisant une banque de pas dédiée.

4.3.1 Faisabilité

Notre étude a permis de montrer la faisabilité de l'ILG dans l'analyse de la marche des patients hémiparétiques post AVC souffrant de PVES. La segmentation du pas automatisée décrite dans la partie 3.2 permet de s'affranchir d'un outil de détection du pas et d'alléger le dispositif. Cette détection a montré un bon niveau de performance dans la détection des pas de sujets atteints de SEP, et de PVES en comparaison au Gold standard. Elle devrait pouvoir être généralisée à un plus grand nombre de cohortes de patients neurologiques. D'autre part, la conception d'un tel algorithme permet d'exploiter directement le signal brut obtenu par les capteurs, sans post traitement ou modifications par un logiciel commercial. Cela fiabilise la détection du pas et permet à n'importe quelle équipe de pouvoir segmenter son signal de marche à l'aide des outils mis en ligne sur Image Processing On Line ³ (Voisard et al., 2023a, 2023b, 2023c).

4.3.2 Utilisation de l'ILG

Afin de permettre une utilisation immédiate et facilement compréhensible par le clinicien de l'ILG dont les indicateurs peuvent être multiples et parfois éloignés de ce que l'œil du clinicien enregistre et analyse, nous avons développé le semiogramme (Voisard et al., 2023d, 2023b). Ce mode de représentation des indicateurs issus du signal d'ILG est présenté sur la Figure 9. Il permet de convertir le signal de marche une fois segmenté en un score visuel d'analyse de la marche séparé en 7 indicateurs cliniques distincts. L'intégration de plusieurs paramètres repartis en critères sémiologiques apporte pour nous un atout majeur dans l'analyse de la marche. En effet cela permet une analyse qualitative plus pertinente que l'utilisation d'un seul paramètre qui a montré ses limites. Cela décompose l'analyse de la marche et permet d'identifier aisément les dimensions altérées de celle-ci. D'autre part l'évolution relative de l'aire du semiogramme permet d'obtenir une variable quantitative facilement comparable d'un temps de mesure à un autre pour évaluer un changement de la

³ <https://www.ipol.im>

marche lors d'un suivi longitudinal d'un même patient. L'aire du semiogramme pondérée par la vitesse moyenne permet une analyse quantitative du rendu visuel du clinicien puisque la comparaison entre les aires des polygones se fait immédiatement et l'ajout du code couleur de la vitesse donne une appréciation globale de la marche. La mesure de l'aire pondérée par la vitesse moyenne a montré une très bonne reproductibilité dans notre étude (de l'Escalopier et al., n.d.). La représentation graphique de cette évolution est d'ailleurs d'un intérêt notable dans le suivi longitudinal des patients comme montré sur la Figure 10.

4.3.3 Apport de l'ILG par rapport à la GAS

Concernant l'évaluation post opératoire du PVES, si la GAS reste l'outil d'évaluation fonctionnelle indispensable et de référence, car elle permet notamment de fixer un contrat fonctionnel raisonnable avec le patient, l'ILG apporte un certain nombre de compléments qui nous paraissent indispensables. Elle permet notamment un suivi longitudinal évolutif, pour suivre les modifications de marche à des temps de mesure différents. En effet la GAS ne permet que de confirmer ou non que le contrat fonctionnel ait bien été rempli. En revanche elle n'objective pas les modifications à plus long terme de ce résultat. D'autre part si la GAS donne une indication directement corrélée à l'intervention, elle occulte le retentissement de celle-ci sur la marche dans son ensemble. Or il apparaît dans notre étude que même en cas de très bon résultat ressenti par le patient, le semiogramme obtenu garde le même profil témoignant du fait que le schéma de marche n'a pas fondamentalement changé, mais que seuls certains critères ont été améliorés. Ces cas de figure confirment que l'objectif de l'intervention ne peut être d'obtenir un semiogramme similaire à ceux des sujets sains. Cette comparaison permet ensuite d'évaluer des mesures associées qui pourront être adoptées pour maximiser le résultat de la chirurgie, comme la rééducation ou les injections de toxine botulique. Une autre application potentielle du semiogramme pourrait être d'offrir au patient un rendu visuel immédiat de sa marche en vue d'obtenir un effet de type biofeedback afin de l'aider à se corriger en temps réel comme cela peut être fait avec la réalité virtuelle par exemple (Kwon et al., 2022; Shideler et al., 2021). Cette approche globale de la marche en fait un indicateur de choix dans le suivi des affections chroniques neurologiques ou rhumatologiques, elle permet un suivi longitudinal automatisé du patient offrant la

possibilité d'un suivi de leur état de santé. Une application possible de l'évaluation quantitative utilisant l'aire du semiogramme pourrait être la comparaison de deux techniques chirurgicales différentes. En effet, compte tenu de la proportion de bons résultats fonctionnels obtenus avec la GAS, l'apport d'une échelle quantitative permet une comparaison plus facilement significative. De nouvelles techniques se développant dans cette indication, une généralisation de l'utilisation de l'ILG pourrait faciliter leur validation (Diner et al., 2023)

4.3.4 Limites de l'ILG

La limite principale de l'analyse ILG réside dans son caractère global. En effet nous n'avons pas voulu chercher à obtenir des données de cinématiques articulaires comme cela a pu être fait dans d'autres études (Pacher et al., 2020). Il s'agit ici d'un indicateur global reflétant la marche dans son ensemble. Les données analytiques précises centrées sur les différentes articulations ne sont pas explicitées avec cette méthodologie. Si l'ILG constitue un bon outil pour évaluer les résultats d'une thérapeutique sur la marche, elle ne permet pas de l'utiliser dans le cadre du bilan préopératoire comme outil d'aide à la planification chirurgicale (Fuller et al., 2002). Pour cela l'AQM reste l'outil de choix.

4.4 Limites de notre étude

Cette étude novatrice présente cependant plusieurs limites. La principale limite concerne la taille faible de l'échantillon de patients étudiés ne permettant pas de réaliser une analyse statistique optimale. Une perspective serait d'élargir cette analyse de la marche au suivi des patients hémiplegiques souffrant de PVES et traités médicalement. Cela permettrait d'avoir une cohorte plus importante avec des tableaux moins sévères, afin d'élargir le champ des patrons de marche observés (Bensmail et al., 2021).

Une autre limite réside dans la faiblesse du score fonctionnel de référence utilisé comme « gold standard ». En effet la GAS est une échelle discrète avec seulement 5 résultats différents, qui ne permet pas un suivi évolutif. Seul le résultat au dernier recul compte. A la

différence des données étudiées dans la cohorte de patients SEP qui ont permis une véritable étude de corrélation.

Enfin le référentiel utilisé dans l'évaluation de la segmentation des pas montre également ses limites dans l'analyse des marches dégradées (Bilney et al., 2003), pour cela une étude comparant AQM et ILG pourrait être complémentaire. La problématique principale restant la caractérisation des marches les plus dégradées dont la structure des pas complique les techniques de détection et de mesure. Une utilisation en routine clinique en neurologie implique une méthode de détection efficace sur les marches dégradées, ce qui reste un véritable challenge (Hendriks et al., 2022; Prasanth et al., 2021; Romijnders et al., 2022).

4.5 Perspectives

Il s'agit ici d'une preuve de concept concernant l'utilisation de l'ILG et du semiogramme. Sa richesse réside dans sa proximité avec la clinique puisqu'il intègre des paramètres directement utilisables par le clinicien permettant une analyse de la marche la plus naturelle possible. Il permet d'y ajouter un caractère reproductible et objectif et une sensibilité infra clinique aux variations de la marche. Il possède toutefois un caractère évolutif, la pertinence des paramètres utilisés devant être éprouvée par de plus grandes cohortes. Une adaptation des critères et paramètres aux pathologies étudiées peut être une possibilité pour permettre de rester le plus proche possible des préoccupations des cliniciens.

5. Conclusion

Notre étude a confirmé la faisabilité et l'intérêt de l'analyse de la marche par ILG dans l'évaluation post opératoire du PVES post AVC en complément de l'analyse fonctionnelle. Le développement d'un algorithme de détection du pas autonome a permis l'utilisation de cet outil en routine clinique. Cette facilité d'utilisation permet un suivi longitudinal objectif et quantifié de la marche chez les patients hémiplésiques post AVC en consultation de routine ne nécessitant pas de locaux ou d'équipe dédiés. L'évaluation du semiogramme sur des cohortes de plus grande ampleur est nécessaire pour en affiner l'utilisation et devrait permettre d'optimiser les indicateurs utilisés.

6. Publications

6.1 Publications dans des revues internationales à comité de lecture

- Sylvain Jung, Nicolas de l'Escalopier, Laurent Oudre, Charles Truong , Eric Dorveaux, Louis Gorintin, Damien Ricard. A Machine Learning Pipeline for Gait Analysis in a Semi Free-Living Environment. *Sensors (Basel)*. 2023 Apr 14;23(8):4000. doi: 10.3390/s23084000. PMID: 37112339; PMCID: PMC10145775.

- Nicolas de l'Escalopier, Cyril Voisard, Mona Michaud, Albane Moreau, Sylvain Jung, Brian Tervil, Nicolas Vayatis, Laurent Oudre, Damien Ricard. Evaluation methods to assess the efficacy of equinovarus foot surgery on the gait of post-stroke hemiplegic patients: A literature review. *Frontiers in Neurology*. 2022 Nov 9;13:1042667. doi: 10.3389/fneur.2022.1042667. PMID: 36438953; PMCID: PMC9683335.

- Nicolas De L'Escalopier, Cyril Voisard, Aliénor Vienne-Jumeau, Albane Moreau, Flavien Quijoux, Flavie Bompaire, Magali Sallansonnet, Marie-Laure Brechemier, Irina Taifas, Camille Tafani, Eve Drouard, Nicolas Vayatis, Damien Ricard and Laurent Oudre. Innovative Multidimensional Gait Evaluation using IMU in Multiple Sclerosis: introducing the semiogram *Frontiers in Neurology* – 2023 Sep 15;14:1237162. doi: 10.3389/fneur.2023.1237162. PMID: 37780706; PMCID: PMC10540441.

6.2 Article en cours de révision dans une revue internationale à comité de lecture

- Nicolas de l'Escalopier, Cyril Voisard, Damien Ricard, Laurent Oudre. Automatic Gait Events Detection with Inertial Measurement Units: Healthy Subjects and Moderate to Severe Impaired Patients. *Journal of NeuroEngineering and Rehabilitation* – under review

- Nicolas de l'Escalopier, Cyril Voisard, Sylvain Jung, Mona Michaud, Albane Moreau, Nicolas Vayatis, Philippe Denormandie, Alix Verrando, Claire Verdaguer, Alain Moussu, Aliénor

Jequier, Christophe Duret, Laurence Mailhan, Laure Gatin, Laurent Oudre, Damien Ricard. Inertial Measurement Units to evaluate the efficacy of Equino Varus Foot surgery in post stroke hemiparetic patients. Journal of NeuroEngineering and Rehabilitation – under review

6.3 Mise en ligne des données et algorithmes utilisés et produits au cours de la thèse

- Cyril Voisard, Nicolas de l'Escalopier, Albane Moreau, Aliénor Vienne-Jumeau, Damien Ricard, Laurent Oudre. A Reference Data Set for the Study of Healthy Subject Gait with Inertial Measurements Units Image Processing On Line – in press <https://www.ipol.im/pub/pre/497/>

- Cyril Voisard, Nicolas de l'Escalopier, Albane Moreau, Aliénor Vienne-Jumeau, Damien Ricard, Laurent Oudre. Automatic Gait Events Detection with IMU: An in-Depth Look at the Algorithm Image Processing On Line – under review

- Cyril Voisard, Nicolas de l'Escalopier, Albane Moreau, Aliénor Vienne-Jumeau, Damien Ricard, Laurent Oudre. Semiogram: a Visual Tool for Gait Quantification in Routine Neurological Follow-UP. Image Processing On Line – under review

6.4 Communications orales présentées lors de congrès internationaux

SNOV 2021 (Symposium of Neuro-Orthopedics in Versailles)

Assessment of equinovarus foot surgery efficacy on poststroke hemiparetic patients' gait: interest of Inertial Measurement Units

SNOV 2023 (Symposium of Neuro-Orthopedics in Versailles)

Nerve transfer in the spastic equino varus foot: anatomical feasibility study

Belgian Foot and Ankle Society advanced course 2021

Gait analysis in orthopedic surgery

6.5 Communications orales présentées lors de congrès français

Société Française de Chirurgie Orthopédique et Traumatologie 2023 :

Prise en charge chirurgicale Neuro-orthopédique du Pied Varus Equin Spastique post AVC : résultats analytiques et fonctionnels.

Société Française de Chirurgie Orthopédique et Traumatologie 2022 :

Évaluation de l'efficacité de la chirurgie du pied varus équin sur la marche des patients hémiplegiques post-AVC : revue de la littérature

SOFAMEA (Société Française d'Analyse du Mouvement de l'Enfant et de l'Adulte) 2022

Assessment of equinovarus foot surgery efficacy on post stroke hemiparetic patients' gait: interest of Inertial Measurement Units

Journée Innovation en Santé de Défense (JISDD) 2022

OrthoWalk : analyse de la marche par AI.

6.6 Communication affichée

Société Française de Chirurgie Orthopédique et Traumatologie 2023 :

Utilisation de l'Inertialo-locographie comme outil d'évaluation de la chirurgie du Pied Varus Équin Spastique sur la démarche des patients hémiplegiques après Accident Vasculaire Cérébral.

7. Annexes

Annexe 1 : Formulaire d'informations et de consentement.



Etude SMARTWALK-AG
Version n° 1.1 du 11/07/2016



NOTE D'INFORMATION

Validation d'un dispositif permettant de suivre l'évolution des performances de la marche

ETUDE SMARTWALK

Promoteur de la recherche : Direction centrale du *Service de Santé des Armées*
Investigateur coordonnateur/principal : Médecin en chef Damien RICARD

Madame, Monsieur,

Votre médecin vous propose de participer à une recherche biomédicale dont la **Direction centrale du Service de Santé des Armées** est le promoteur. Avant de prendre une décision, il est important que vous lisiez attentivement cette page qui vous apportera les informations nécessaires concernant l'objectif de cette recherche. N'hésitez pas à poser toutes les questions que vous jugerez utiles à votre médecin.

Votre participation est entièrement volontaire. Si vous ne désirez pas prendre part à cette recherche, vous continuerez à bénéficier de la meilleure prise en charge médicale possible, conformément aux connaissances actuelles.

Quel est l'objectif de cette recherche?

Nous menons une étude ayant pour objectif d'évaluer l'intérêt de l'utilisation d'une mesure globale de votre marche, en analysant l'impact des différents troubles d'origine cérébrale pouvant avoir été diagnostiqués par votre médecin. Si vous décidez de participer à cette étude nous allons, lors de votre consultation, réaliser l'enregistrement d'un exercice de marche sur 10m aller-retours avec des petits capteurs inertiels (accéléromètres et gyromètres, l'ensemble étant d'une taille inférieure à une boîte d'allumettes) que nous placerons à vos pieds, ceinture, poignets, et front. Vous porterez également une paire de lunettes nous permettant de suivre votre regard, ainsi que deux capteurs pour suivre vos battements cardiaques et l'activité de votre système nerveux autonome (sueur, température de votre peau). Cet examen ne présente aucun caractère douloureux. L'ensemble des mesures est réalisé en 15 minutes par un infirmier de recherche clinique.

Il ne vous sera pas demandé de visites supplémentaires à l'hôpital si vous participez à cette recherche.

Après avoir lu cette note d'information, n'hésitez pas à poser à votre médecin toutes les questions que vous désirez. Après un délai de réflexion, si vous acceptez de participer à cette recherche, vous devez compléter et signer le formulaire de consentement de participation. Un exemplaire du document complet vous sera remis.

Merci de votre attention.

FORMULAIRE DE CONSENTEMENT

Validation d'un dispositif permettant de suivre l'évolution des performances de la marche

ETUDE SMARTWALK

Promoteur de la recherche : Direction Centrale du Service de Santé des Armées

Investigateur coordonnateur/principal : Professeur Damien RICARD

Je soussigné(e)..... (nom, prénom) certifie avoir lu et compris la note d'information qui m'a été remise. J'accepte de participer à une mesure de ma marche sur 10m aller-retour en portant des capteurs embarqués (six capteurs de mesures inertiels, une paire de lunettes pour suivre mon regard, un capteur pour mesurer mes battements cardiaques et un capteur pour mesurer ma température corporelle et ma sudation).

J'ai eu la possibilité de poser toutes les questions que je souhaitais au Pr (nom, prénom) qui m'a expliqué la nature, les objectifs, les risques potentiels et les contraintes liées à ma participation à cette recherche.

Je connais la possibilité qui m'est réservée d'interrompre ma participation à cette recherche à tout moment sans avoir à justifier ma décision et je ferai mon possible pour en informer le médecin qui me suit dans la recherche. Cela ne remettra naturellement pas en cause la qualité des soins ultérieurs.

J'ai eu l'assurance que les décisions qui s'imposent pour ma santé seront prises à tout moment, conformément à l'état actuel des connaissances médicales.

Je suis informé(e) que la possibilité qu'une partie des mesures effectuées à l'occasion de ce protocole de recherche soit conservée pour une utilisation ultérieure à des fins de recherche. J'ai également été informé(e) de mon droit à m'opposer à ce que cette conservation et cette utilisation ultérieure à des fins de recherche aient lieu.

J'ai pris connaissance du fait que cette recherche a reçu l'avis favorable du CPP Nord Ouest III en date du 01/07/2017, et a fait l'objet d'une déclaration à la Commission Nationale de l'Informatique et des Libertés (CNIL), selon la réglementation en vigueur (MR001). J'accepte que les données enregistrées à l'occasion de cette recherche puissent faire l'objet d'un traitement informatisé sous la responsabilité du promoteur et je dispose également d'un droit d'opposition à la transmission des données couvertes par le secret professionnel susceptibles d'être utilisées dans le cadre de cette recherche et d'être traitées. Ces droits s'exercent auprès du médecin qui me suit dans le cadre de cette recherche et qui connaît mon identité.

L'Etat, lorsqu'il a la qualité de promoteur, est soumis aux obligations incombant à l'assureur. Il assume l'indemnisation des conséquences dommageables de la recherche biomédicale pour les personnes qui s'y prêtent et celles de ses ayants droits.

Ayant disposé d'un temps de réflexion suffisant avant de prendre ma décision, j'accepte librement et volontairement de participer à la recherche ayant pour objectif la validation d'un dispositif permettant de suivre les performances de stabilisation statique
 oui non

Je pourrai à tout moment demander des informations complémentaires au médecin qui m'a proposé de participer à cette recherche, n° téléphone :

Fait à Clamart le 04/10/2017

Fait à Clamart le 04/10/2017

Signature du patient/sujet :

Signature du médecin

[Signature area for patient]

[Signature area for doctor]

- 1^{er} feuillet (original) : à conserver à part par l'investigateur pendant 30 ans dans un lieu sûr fermé à clé
- 2^{ème} feuillet : à remettre au patient/sujet après signatures
- 3^{ème} feuillet : à ranger dans le classeur investigateur, il sera demandé ultérieurement par le promoteur



Etude SMARTWALK-AG
Version n° 1.1 du 11/07/2016



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