Spatiotemporal Parameters And Gait Variability In People With Psoriatic Arthritis (Psa) : A Cross-Sectional Study.

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Research Article

Keywords: Psoriatic arthritis, foot pain, foot function, spatiotemporal parameters, gait variability, gait analysis.

Posted Date: December 1st, 2021

DOI: https://doi.org/10.21203/rs.3.rs-883851/v1

Version of Record: A version of this preprint was published at Journal of Foot and Ankle Research on March 4th, 2022. See the published version at https://doi.org/10.1186/s13047-022-00521-y.

Abstract

Background: Foot involvement is a major manifestation of psoriatic arthritis (PsA) and could lead to severe levels of foot pain and disability and impaired functional mobility and quality of life. Gait spatiotemporal parameters (STPs) and gait variability, used as a clinical index of gait stability, have been associated with several adverse health outcomes including risk of falling, functional decline, and mortality in a wide range of populations. Previous studies showed some alterations in STPs in people with PsA. However, gait variability and the relationships between STPs, gait variability and self-reported foot pain and disability have never been studied in this populations. Body-worn inertial measurement units (IMUs) are gaining interest in measuring gait parameters in clinical settings.

Objectives: To assess STPs and gait variability in people with PsA using IMUs and, to explore their relationship with self-reported foot pain and function and to investigate the feasibility of using IMUs to discriminate patient groups based on gait speed-critical values.

Methods: 21 participants with PsA (Age: 53.9 ± 8.9 yrs; median disease duration: 6 yrs) and 21 age and gender-matched healthy participants (Age 54.23 ± 9.3 yrs) were recruited. All the participants performed three 10-meter walk test trials at their comfortable speed. STPs and gait variability were recorded and calculated using six body-worn IMUs and the Mobility Lab software (APDM®). Foot pain and disability were assessed in participants with PsA using the foot function index (FFI).

Results: Cadence, gait speed, stride length, and swing phase, were significantly lower, while double support was significantly higher, in the PsA group ($p < 0.006$). Strong correlations between STPs and the FFI total score were demonstrated ($|r| > 0.57$, $p < 0.006$). Gait variability was significantly increased in the PsA group, but it was not correlated with foot pain and function ($p < 0.006$). Using the IMUs three subgroups of participants with PsA with clinically meaningful differences in self-reported foot pain and disability were discriminated.

Conclusion: STPs were significantly altered in participants with PsA which could be associated with self-reported foot pain and disability. Future studies are required to confirm the increased gait variability highlighted in this study and its potential underlying causes. Using IMUs in clinical settings has been useful to objectively assess foot function in people with PsA.

Study registration:

ClinicalTrials.gov, NCT05075343, Retrospectively registered on 29 September 2021.

1. Background:

Psoriatic arthritis (PsA) is a chronic inflammatory arthropathy associated with skin psoriasis and belongs to the spondyloarthropathies family. During the disease course, several musculoskeletal manifestations with both axial and peripheral joint involvement can occur. The foot and the ankle, are particularly

common targets of inflammation and their involvement could be the first and major manifestation of the disease in a large proportion of the patients [1]. Foot and ankle problems include dactylitis, enthesitis, synovitis, and tenosynovitis that can manifest as foot and/or ankle pain, stiffness, swelling, and deformity [2–6]. Consequently, a high proportion of patients experience moderate to high foot impairment which can impact activities of daily living that require good foot function such as walking [2, 7, 8].

Pain and physical function are identified among the most important clinical domains in PsA [9]. While patient-reported outcomes are commonly used to assess pain and perceived function, gait analysis has been widely used as a tool to obtain an objective measure of physical function in different populations. In people with inflammatory joint disease including rheumatoid arthritis (RA) and PsA, different gait parameters of varying complexity such as joint kinetics and kinematics, plantar pressure, and spatiotemporal parameters (STPs) have been employed to assess either global function or localized foot function [10][11][12]. Among these parameters, STPs which typically encompass gait speed, stride length, cadence, double support, and swing time, present certain ease of interpretability by both clinicians and patients and have a great utility in predicting health outcomes. For example, a reduced gait speed was associated with an increased risk of falling [13], functional decline [14], and mortality in older adults [15]. Gait speed was also designated as the 6th vital sign and precise cut-off values have been used to predict specific outcomes in a wide range of populations [16, 17]. Both the STPs mean values and the variation around them, referred to as gait variability, are key metrics in gait evaluation [18]. Gait variability is used as a clinical index for gait stability [19] and was associated with an increased risk of falling in older adults [20].

Importantly, STPs and gait variability can now easily be measured with the emerging lightweight, low cost, and easy-to-use wearable Inertial measurement units (IMUs). These latter have shown acceptable accuracy and precision in measuring STPs in people with PsA and axial spondyloarthritis [21, 22].

A great number of studies investigated gait STPs in people with RA with foot involvement and showed significant alterations in gait STP which included reduced gait speed, stride length and cadence, and increased double support [12]. However, there is scarce data on gait STPs in people with spondyloarthritis including PsA [12][23][24]. A recent study demonstrated changes in gait STPs including reduced gait speed, stride length, and swing time and increased double support time which were associated with self-reported pain in people with axial spondyloarthritis [25]. Similar changes were reported in a few studies in people with PsA [3][26][27]. For instance, Hyslop et al. assessed cadence, gait speed, stride length, and double support time in people with PsA with and without enthesitis and showed that stride length was significantly lower in the PsA group with enthesitis [26]. A study by Woodburn et al. which was based on the same cohort as Hyslop et al.'s showed a significant decrease in gait speed in a PsA group with enthesitis compared to healthy controls [27]. Wilkins et al. investigated cadence, gait speed, and double support time in people with PsA with and without active dactylitis. Their findings showed a decreased gait speed and increased double support in both PsA groups. However, no significant differences were demonstrated compared to the control group. This could be explained by the small sample size, the

relatively young mean age of the study participants (36.7 ± 21.5 years) and the short disease duration (4.6 ± 6.7 years) which previously shown to be correlated with gait parameters in people with RA [3][28].

Overall, the above studies demonstrate alterations in gait STPs. However, despite including participants with confirmed foot involvement, it is not clear if altered gait STPs are associated with self-reported foot pain and disability. On another note, the reported alterations could be indicative of increased gait instability since such changes are characteristics of cautious gait patterns that are typically undertaken by older adults to increase stability [29]. In fact, a few recent studies demonstrated altered static and dynamic balance [30][31] and increased risk of falling in people with PsA [32]. Fall-related risk factors have not been studied in people with PsA. Nevertheless, research in RA showed that swollen and tender lower extremity joints were among the most significant fall-related risk factors [33]. Taking all this into account, despite being a relevant and easy to measure gait parameter, no previous research investigated gait variability and its relationship with self-reported foot pain and function in people with PsA.

Thus, given the limited evidence regarding STPs, gait variability, and their relationship with foot pain and disability in people with PsA, this study aimed 1) to investigate STPs and gait variability in participants with PsA with foot pain and compare them to age and sex-matched healthy participants using body-worn IMUs, 2) to explore the relationship between STPs, gait variability, and self-reported foot pain and disability, and 3) to investigate the feasibility of using body-worn IMUs to discriminate patients groups based on gait speed-critical values.

2. Methods:

2.1. Study Design:

A portion of the data presented in this descriptive cross-sectional study pertains to an ongoing pre-experimental trial exploring the effects of custom-made foot orthoses on foot pain and function, and gait STPs in people with PsA. Baseline gait STPs measures in participants with PsA captured during a standardized 10-meter walk within this pre-experimental study were compared to age and sex-matched controls undergoing the same clinical gait evaluation protocol.

2.2. Participants:

Twenty-one participants with PsA were consecutively recruited from the rheumatology outpatient clinics at the Hotel Dieu University Hospital CHU of Sherbrooke (CHUS). Inclusion criteria were the following: being between 20 and 70 years of age, having a rheumatologist-confirmed PsA diagnosis, having recurrent, moderate to severe foot pain defined using a 3-point cut-off on a 0 to 10 numerical rating scale [34], and receiving stable medication for at least the three months preceding the recruitment. Exclusion criteria applied to patients with diabetes, neurological disease, or any musculoskeletal disease that could impact normal gait patterns. Patients who received intra-articular corticosteroid injections or any conservative foot treatment such as foot orthoses within the past three months were excluded as they

may influence their gait. Twenty-one control participants matched for age and sex with no self-reported foot/ankle problems were also recruited using flyers posted in the research center and the word-of-mouth strategy. They had to be devoid of a current or recent history of foot/ankle pain and self-reported gait deficits. The study was approved by the CIUSSS de l'Estrie-CHUS Institutional Review Board (IRB) and all the participants provided written informed consent.

2.3. Data Collection Procedure:

Upon their arrival at the Université de Sherbrooke Research center on Aging, demographic data including sex, age, body mass index (BMI), and foot and lower limb pain were obtained for all participants (PsA and controls). Perceived foot function was additionally assessed in PsA participants. Afterward, an instrumented gait analysis was performed for each participant (PsA and controls). Disease-related information was obtained for participants with PsA from their medical records.

2.4. Outcomes And Measurement Tools:

• Clinical parameters:

Disease characteristics:

Disease duration, current medication, and C-reactive protein (CRP) levels, as a marker of systemic inflammation, were obtained from the patient's medical record. Pain sites and deformities at the feet were documented from a podiatrist clinical examination record.

Foot And Lower Limb Pain:

Given that lower limb and the lower back pain are not uncommon in people with PsA and that they could affect gait patterns [25, 35–38], we assessed knee, hip, and lower back pain in addition to foot pain, using the numerical rating scale (NRS) in participants with PsA and healthy controls. Participants were asked to circle a number between 0 and 10 that fits best their average pain intensity experienced in the foot, knee, hip, and lower back over the seven days preceding the data collection.

Foot Function:

Foot function was measured in the PsA group with the **Foot Function Index (FFI)**, a reliable and valid questionnaire that has been proven suitable for use in people with foot disorders and a low functioning status [39, 40]. The FFI was chosen to be used in this study because it has a validated version in French. The FFI comprises 23 items divided into three subscales measuring foot pain (FFI-Pain), foot disability (FFI-Disability), and foot-related activity limitation (FFI-Activity Limitation). Each FFI item is recorded on

an NRS (0 to 10). A total score and three sub-scale scores were calculated. For an easier interpretation, we present the scores as percentages where a higher percentage indicates higher levels of foot pain and related disability.

• Gait Analysis:

Gait STPs presented and defined in Table 1 and Figure 1a [41], were measured in participants with PsA and healthy controls using Opal IMUs and the Mobility Lab software (APDM Wearable Technologies, Portland, OR, USA). Mobility Lab is a research-grade system widely used by researchers and clinicians for gait and balance analysis. Mobility Lab has been validated in healthy and pathological populations such as Parkinson's disease [42–44]. The accuracy of this system was also assessed in people with PsA in a previous work that showed acceptable errors in measuring gait STPs recorded over a treadmill at a normal walking speed [21]. Mobility Lab includes a set of six IMUs each with a triad of sensors (a 3-axis accelerometer, a 3-axis gyroscope, and a 3-axis magnetometer) (Figure 1. C), an access point for wireless data transmission and synchronization and, a software (Mobility Lab) that provides an automated estimation of several STPs (Table 1). Details on the algorithm allowing for STPs calculation with the Mobility Lab system have been previously described [45].

All the participants performed three trials of the 10 meters walk test (10MWT) (Figure 1. B) which consists of walking over a 14-meters straight walkway at a comfortable speed. Two extra meters at the beginning and the end of the trials were added to account for the acceleration and deceleration and only the central 10 meters were considered for the analysis (Figure 1. B). The participants were asked to walk at their usual preferred self-selected speed wearing comfortable walking shoes and none of the participants used foot orthoses or modified footwear. The Mobility Lab IMUs were fixed with elastics straps on the chest, the lower back, and both wrists and feet as recommended by the manufacturer's instructions (Figure 1. C).

Stride time variability was chosen as a measure of gait variability as it is the most commonly reported parameter in clinical studies [46]. This metric was calculated as the coefficient of variation (CV) defined as the percentage of each participant's standard deviation of stride time divided by its mean value:

$$\mathrm{CV} = \frac{\mathrm{SD}}{\mathrm{Mean}} \mathrm{x100\%}$$

Table 1
Gait Spatiotemporal Parameters (SPTs), measurement units, and definitions.

Variables	Units	Definitions
Cadence	Step/minute (step/min)	Number of steps per minute
Gait speed	Meter/second (m/s)	The forward speed of the subject, measured as the forward distance traveled during the gait cycle divided by the gait cycle duration.
Stride length	Meters (m)	The forward distance traveled by a foot during a gait cycle.
Double support time	% Gait cycle time (GCT)	The percentage of the gait cycle in which both feet are on the ground.
Swing time	% GCT	The percentage of the gait cycle in which the foot is not on the ground.
Foot strike angle	degrees	The angle of the foot dorsiflexion at the point of initial contact. The pitch of the foot when flat is zero and positive when the heel contacts first.
Stride time variability	%	The percentage of each participant's standard deviation of stride time is divided by the same parameter mean value.

GCT gait cycle time

Definitions were provided by [47]

2.5. Statistical analysis:

Based on data from a previous study comparing gait parameters between people with PsA diagnosed with rearfoot enthesitis and healthy controls [26], an average effect size was calculated from the means and standard deviations reported for cadence, gait speed, stride length, and double support time. Given the calculated effect size (d=0.8), a total sample size of 32 participants (16 per group) was required to detect significant differences in gait STPs with paired T-test at an α of 0.01 and a power of 0.95.

The Shapiro-Wilk test was used to examine data distribution. Paired t-tests and the Wilcoxon signed-rank test were used to assess the differences in gait STPs and stride time variability between participants with PsA and matched healthy controls, and Cohen's effect size was calculated to quantify the magnitude of these differences. ANCOVA was used to adjust the differences in STPs between PsA and healthy participants for the effect of BMI. Pearson's and Spearman's correlation coefficients were calculated to assess the relationships between STPs, gait variability, and self-reported foot pain and function in participants with PsA. Correlation coefficients were considered weak, moderate and strong for values between 0.1 and 0.3, 0.3 and 0.5, and > 0.5, respectively [48]. Given the clinical relevance of gait speed and the availability of reference values for this metric, subgroups of participants with PsA were differentiated based on critical values of gait speed (1.0 m/s: the limit below which gait speed values are

associated with higher mortality and 1.2 m/s: the lower limit of the confidence interval for normative gait speed [15][49]). The relation between gait speed, FFI total score and FFI subcategories scores for these three subgroups were visualized in scatter plots.

As we tested multiple variables that may be highly correlated, we used the Bonferroni correction method to reduce type I error resulting from multiple testing. Therefore, P values < 0.006 were considered statistically significant. Analyses were performed using the SPSS version 26.0 (IBM SPSS, Armonk, NY).

3. Results:

3.1. Demographics and clinical characteristics:

Twenty-one participants with PsA (5 males, 16 females) with a mean age of 53.9 ± 8.9 years and a mean disease duration of 11.5 ± 10.2 years and 21 healthy controls (5 males, 16 females) with a mean age of 54.2 ± 9.3 years were included (Table 1). BMI was significantly higher in participants with PsA compared to healthy controls (29.3 ± 4.5 vs 24.4 ± 3.4), $p < 0.001$). Because of the different thresholds used by the laboratories, CRP levels are reported as normal or high. CRP levels were missing, high and normal for 4, 1 and 16 participants, respectively. Ninety percent of the patients were treated with disease-modifying anti-rheumatic drugs (DMARD) and/or biological therapy.

Moderate to severe levels of lower limb pain, and moderate to severe levels of self-reported foot pain (55.7 ± 18.3) and disability (44.6 ± 22.7) were reported in participants with PsA while foot and lower limb pain levels were close to zero in healthy participants (Table 2). The most frequently reported pain sites at the feet were the ankles followed by the metatarsals, toes, and heels, and 18 (85%) participants had simultaneous forefoot and rearfoot pain. Sixty-tow percent of the participants in the PsA group had heel valgus, 67% had hammer/claw toes and 24% and 19% has hallux valgus and hallux rigidus respectively.

Table 2
Demographics and clinical characteristics of participants with PsA and healthy participants.

Variables	PsA	CONTROLS
	Mean ±SD	Mean ± SD
AGE (years)	53.9 ± 8.9	54.23 ±9.3
BMI (kg/m$^{2)}$	29.3 ± 4.5)	24.4 ± 3.4*
SEX (M : F)	5 : 16	5 : 16
DISEASE DURATION (years)	11.5 ±10.2 (Median = 6)	-
CRP (mg/l)	16 (94%)	
o Normal	1 (6%)	
o High		
Pharmacological therapy		
o DMARDs	6 (30%)	
o Biological therapy	5 (25%)	
o DMARDs and Biological therapy	7 (35%)	
Foot pain (0 to 10 points)	5.6 ± 1.9	0.2 ± 0.6*
Knee pain (0 to 10 points)	4.7 ± 2.6	0.5 ± 1.2*
Hip pain (0 to 10 points)	4.8 ± 2.9	0.1 ± 0.3*
Lower back pain (0 to 10 points)	5.4 ± 2.7	1.6 ± 2.5*
Foot function Index		
o FFI-Pain (%)	55.7 ± 18.3	-
o FFI-Disability (%)	44.6 ± 22.7	
o FFI-Activity limitation (%)	34.3 ± 24.4	
o FFI-Total (%)	47.02 ± 18.3	
Pain sites		-
o Toes	15 (71%)	
o Metatarsals	16 (76%)	
o Heels	11 (52%)	
o Ankles	17 (81%)	

Variables	PsA	CONTROLS
Deformities		-
o **Rearfoot valgus**	13 (62%)	
o **Hallux valgus**	5 (24%)	
o **Hallux rigidus**	4 (19%)	
o **Hammer/claw toes**	14 (67%)	

Values are mean ± standard deviation and percentages for categorial variables, p values < 0.006 are considered significant, *: p < 0.006. BMI body mass Index, M males, F females, FFI foot function index

3.2 Spatiotemporal parameters and gait variability in PsA and healthy participants:

Gait STPs for left and right foot in PsA and healthy participants are presented in Table 3. There were significant differences between the two groups in all the measured STPs except for the foot strike angle of the right foot. STPs averaged for left and right foot, and stride time variability adjusted for BMI in PsA and healthy participants are summarized in Table 4. Before adjusting the data for BMI, all STPs except for foot strike angle were significantly different between groups. Cadence, gait speed and stride length and swing time were significantly lower in participants with PsA, and large effect sizes are reported ($p < 0.006$; $1.08 < d < 1.3$) (Table 4). Gait cycle duration and double support time were significantly higher in the PsA group and large effect sizes were also reported ($p < 0.006$; $d= 1.2$ and $d= 1.26$) (Table 4). After adjusting the differences for BMI, only cadence, gait cycle duration, and gait speed remained significantly different between groups whilst the differences in stride length ($p=0.026$), double support ($p=0.022$), and swing time ($p=0.023$), were no longer significant. Stride time variability was significantly higher in the PsA group before and after adjusting the differences for BMI ($p=0.001$ and $p= 0.005$) and a moderate effect size was reported ($d= 0.68$) (Table 4).

Three subgroups of participants with PsA (PsA1, PsA1, and PsA3) were differentiated based on gait speed-critical values. Patients in PsA1 had gait speed values below 1.0 m/s with a mean gait speed of 0.81 ± 0.16 m/s; PsA2 included patients with gait speed values comprised between 1.0 m/s and 1.2 m/s and the mean gait speed for this subgroup was 1.08 ± 0.05 m/s and PsA3 was composed of patients with gait speed values superior to 1.2 m/s with a mean gait speed of 1.34 ± 0.1 m/s. PsA1, PsA2 and PsA3 represented 32%, 41% and 27% of the total sample, respectively.

Table 3
Spatiotemporal parameters (STPs) for left and right foot in participants with PsA and healthy matched controls:

Variable	PsA participants		Control participants		p-value	
	Left	Right	Left	Right	Left	Right
Cadence (step/min)	108.1 ± 10.8	107.7 ±10.8	120 ± 6.8	119.9 ± 6.9	0.000	0.000
Gait cycle duration (s)	1.1 ± 0.1	1.1 ± 0.1	1 ± 0.1	1 ± 0.1	0.000	0.000
Gait speed (m/s)	1.1 ± 0.2	1.1 ± 0.2	1.4 ± 0.2	1.3 ± 0.2	0.000	0.000
Stride length (m)	1.2 ± 0.2	1.2 ± 0.2	1.4 ± 0.2	1.3 ± 0.1	0.001	0.001
Double support time (% GCT)	21.9 ± 4.1	22.1 ± 4.1	17.8 ± 2.7	18 ± 2.7	0.000	0.000
Swing time (% GCT)	39.4 ± 1.9	38.6 ± 2.4	41.3 ± 1.4	40.8 ± 1.4	0.001	0.000
Foot strike angle (degrees)	25.3 ± 4.1	24.7 ± 3.9	28.6 ± 2.7	27.7 ± 3.7	0.008	0.015

Values are Mean ± standard deviation, p values < 0.006 are considered significant.

PsA Psoriatic arthritis, *GCT* gait cycle time

3.3 Relationship between STP, gait variability, and clinical parameters:

Correlation coefficients between STPs, stride time variability and, clinical parameters in participants with PsA are presented in Figure 2. All the STPs were strongly and significantly correlated to the FFI total score and the disability sub score ($0.57 < |r| < 0.87$, $p < 0.006$). All the STPs except for cadence and gait cycle duration, were correlated to the pain and activity limitation sub scores ($0.63 < |r| < 0.8$, $p < 0.006$) (Figure 2). Gait speed had the highest correlation coefficients with the FFI total score ($r= -0.87$) and the disability sub score ($r = -0.78$) while foot strike angle had the highest correlations with the pain sub score (FFI-Pain) ($r = -0.71$). Swing time ($r = -0.80$) had the highest correlations with the activity limitation sub score (FFI-Activity limitation). Regarding gait variability, there was no significant correlation between stride time CV and clinical parameters of foot pain and disability.

The relations between gait speed and the total FFI score and sub scores for PsA subgroups (PsA1, PsA2, and PsA3) are presented in Figure 3. Participants in PsA1 had the highest scores on all the subscales and the total FFI compared to PsA2 and PsA3 (FFI-Total: 62.21 ± 11.36% for PsA1, vs 48.68 ± 12.36% and 26.83 ± 11.14% for PsA2 and PsA3, respectively). Knowing that the minimal clinically important difference (MCID) for the FFI total score is equal to 7%, the differences in the FFI total scores found between these subgroups, were clinically meaningful.

We theorized that CRP levels, disease duration, knee pain, hip pain, and lower back pain would affect STPs and interfere with their relationship with the FFI. However, none of these potential confounders was

correlated with STPs except for knee pain which was moderate with foot strike angle (r = -0.48, p = 0.028) but the strength of the relationship did not reach the significance level.

Table 4
Spatiotemporal parameters (STPs) averaged for left and right foot and stride time variability in participants with PsA and healthy matched controls before and after adjustment for BMI.

Variables	PsA participants		Control participants		Cohen's d
	Mean ± SD	Adj Mean (SE)	Mean ± SD	Adj Mean (SE)	
Cadence (step/min)	107.91 ± 10.78	107.47 (2.12)	120.08 ± 6.8*	120.55 (2.17) †	1.3
Gait cycle duration (s)	1.13 ± 0.14	1.13 (0.03)	1.00 ± 0.06*	1.00 (0.03) †	1.2
Gait speed (m/s)	1.07 ± 0.23	1.10 (0.05)	1.35 ± 0.2*	1.38 (0.06) †	1.3
Stride length (m)	1.17 ±0.18	1.19 (0.04)	1.34 ± 0.13*	1.32 (0.04)	1.08
Double support (% GCT)	22.00 ± 4.13	21.43 (0.79)	17.95 ± 2.7*	18.55 (0.81)	1.16
Swing time (% GCT)	39.0 ± 2.08	39.28 (0.40)	41.03 ± 1.36*	40.73 (0.41)	1.15
Foot strike angle (degrees)	24.99 ± 3.79	25.16 (0.80)	28.15 ± 2.97*	27.97 (0.82)	0.92
Stride time variability (%)	4.03 ± 3.56	4.49 (0.58)	2.32 ± 0.72*	1.84 (0.60) †	0.68

Values are mean ± standard deviation and adjusted mean (Standard error)

PsA Psoriatic arthritis, *Adj* adjusted mean, *SE* Standard error, *d* Cohen's effect size, *GCT* gait cycle time

* Significant differences in mean values between PsA and healthy participants

† Significant differences in adjusted mean values between PsA and healthy participants

4. Discussion:

The aims of this study were first to assess the differences in gait STPs and gait variability measured with IMUs during a 10-meter walk test between participants with PsA with foot pain, and age and sex-matched healthy participants and second, to investigate the relationships between gait STPs and variability and clinical outcomes of foot pain and disability.

Spatiotemporal parameters:

Our findings showed significant differences in all the STPs between participants with PsA and matched controls. These differences included lower cadence, gait speed, stride length, swing time, and foot strike angle and, higher gait cycle duration and double support time in the PsA group compared to the healthy controls. However, only cadence, gait speed, and gait cycle duration remained significantly different after adjusting the differences for BMI. Nearly 50% of our PsA sample had a BMI above 30 kg/m^2 which is not surprising because obesity is an important comorbidity of PsA [50]. Moreover, obesity is known to alter STPs which has been suggested to be a strategy to lower joint loadings [51]. Therefore, it is logical that BMI affected the differences in STPs between participants with PsA and controls in our study.

A few previous studies showed some alterations in STPs in people with PsA but not all of them demonstrated significant differences between PsA participants and healthy controls. For instance, Woodburn et al. demonstrated a significant decrease in gait speed in people with PsA with enthesitis ($p= 0.014$) [27]. Hyslop et al. showed that except for stride length, there were no significant differences in cadence, gait speed, and double support time, between participants with PsA with enthesitis and healthy controls [26]. Similarly, Wilkins et al. reported no significant differences in cadence, gait speed, and double support time in PsA with and without dactylitis compared to healthy participants [3]. It is important to mention that all these studies included participants with a younger mean age compared to that reported in our study. In a recent systematic review, age has been shown to have significant effects on STPs in healthy adults [29]. Thus, the more significant between-group differences demonstrated in the present study could be attributed to a combined effect of age and disease. Moreover, in the study by Hyslop et al. the participants were matched for BMI which was normal in PsA and control participants. This could explain the non-significant differences reported in their findings. In addition, in this latter study, even though patients with confirmed enthesitis were included, low to moderate levels of foot pain were reported by the authors which can also help explain their findings. In our study, although nearly 90% of the PsA participants were managed on DMARDs/biologicals and most of them had normal CRP levels, a high prevalence of simultaneous forefoot and rearfoot pain and moderate to severe levels of self-reported foot pain and disability were demonstrated. Clinically important differences in STPs between PsA and healthy participants and strong correlations between foot pain, foot function, and STPs, especially gait speed, were also demonstrated. Interestingly, these correlations were not affected by the CRP levels, disease duration, and lower limb pain since none of these clinical parameters was significantly correlated to STP. Although direct comparison between pain levels reported in Hyslop et al. and those reported in the present study cannot be done due to the different measurement tools used, our findings suggest that foot pain may play a major role in gait alterations in people with PsA.

Based on gait speed values, we were able to discriminate between three PsA subgroups. PsA participants who had gait speed values below 1.0 m/s, had higher FFI scores than those for whom gait speed was comprised between 1.0 m/s and 1.2 m/s and those with gait speed above 1.2 m/s. We didn't have enough power to statically test the differences in the FFI scores between these three subgroups. However, knowing that the MCID for the FFI total score is 7 points, we were able to show that differences between these gait speed-based subgroups could be clinically significant. This suggests that gait speed may be a

relevant metric not only to assess gait alteration in people with PsA but also to have more objective insight into the impact of the disease on self-reported foot pain and disability.

Results from studies addressing gait STPs in patients with RA are coherent with our study. For example, a previous systematic review on gait analysis of the lower limb in patients with RA showed they tend to walk slower, with a longer gait cycle, a shorter step length, a longer double support time, and a lower cadence compared to healthy subjects [52]. These findings were confirmed in a recent metanalysis that reported a significant decrease in gait speed, stride length, and cadence and a significant increase in double support in patients with RA compared to healthy participants. Similarly to the present study, this metanalysis also reported large effect sizes for the differences between RA and healthy participants (Effect size (95% CI) were 1.55 (0.83 to 2.27); 1.66 (1.49 to 1.84); 0.97 (0.45 to 1.49)) and 1.01 (0.66 to 1.36) for gait speed, stride length, cadence and double support time, respectively [12].

It appears that, walking slower with shorter steps is a common compensatory strategy that people with arthritic foot disease use to reduce loads and pain in the affected joints and to increase stability [51][53, 54]. It has been reported that reducing gait speed leads to lower joint flexion and extension moments in hip, knee, and ankle joints [55] and that reducing step length allows for a decrease in the vertical ground reaction forces [56–58]. Moreover, double limb support in contrast to single limb support and swing (% GCT), is the most stable phase during gait and all these parameters represent the ability of the patient to transfer their body weight on the affected limb [59]. Our findings, similarly to previous studies in RA patients showed a significant increase of double support and a reduction in the swing phase [12]. This suggests that spending more time on both feet could be an adaptive approach to increase stability and reduce pain during gait.

Gait Variability:

Analysis of gait variability is a clinically relevant parameter in the evaluation of gait and responses to interventions and is a viable option for the quantitative evaluation of gait stability [19]. To our knowledge, gait variability has never been investigated in people with PsA or other populations with foot involvement associated to arthritic joints disease. In our study, the mean stride time variability was higher in the PsA goup (4.49 ± 3.56%) compared to the control group (2.32 ± 0.72%), and above the normative values reported for stride time variability (1.1–2.6%) [46] indicating an increased gait instability. This is consistent with novel findings from a recent study that reported an increased risk of falling in people with PsA [32]. Increased gait variability and instability could be ascribed to pain, muscles weakness, restricted range of motion, and a decrease of proprioception caused by inflammation in the foot joints and the surrounding structures [18]. However, we did not find significant correlations between foot pain and stride time variability. Findings from a recent study reporting a significant alteration of static and dynamic balance in people with PsA, also showed that there were no correlations between balance parameters, foot pain and foot function [31]. This suggests that pain may not be a determinant of gait variability and that this metric could be accepted as an independent gait parameter that should be assessed

systematically in people with PsA. However, this needs to be confirmed in larger and longitudinal studies. Further studies are also needed to investigate the involvement of muscle weakness, reduced range of motion, and alterations of the proprioceptive system in gait variability.

Clinical Perspectives:

Our study showed that none disease-related parameters (disease duration and CRP levels) were not correlated with self-reported foot pain and function which is consistent with results from a previous study conducted in people with spondyloarthritis [60]. Gait spatiotemporal parameters and especially gait speed, however, were strongly correlated to these clinical outcomes. It would be interesting to investigate these associations in larger and longitudinal studies. It would be also relevant to assess the associations between gait parameters and important clinical domains such as disease activity, global function, and fatigue.

Body-worn IMUs for gait analysis are more than ever used in clinical assessment and clinical studies in several neurological diseases such as Parkinson's disease, stroke, multiple sclerosis, and other conditions that increase the risk of falling. These systems are easy to use, time and cost-effective, do not require special equipment or expertise, could be used in any setting and recent evidence suggests that they could accurate and reliable to measure STPs in people with axial spondyloarthritis and PsA [21, 22]. This study suggests that body-worn IMUs could be useful to obtain an objective measure of functional mobility in people with PsA.

There are some limitations to this study. First, given the small sample size and the uneven distribution of males and females in our study sample, we cannot generalize the findings to the population. Second, we included patients based on their subjective perception of foot involvement. Although from a clinical perspective, the patients' perception of pain and disability is a vital criterion, adding ultrasonography/MRI data to confirm the presence of enthesopathy, tendinopathy, synovitis, and /or bone erosions would have given more insight into the severity and progression of foot involvement. Third, CRP levels were documented from the participant's clinical records which led to missing data and a delay (up to 3 months in a few participants) between CRP levels assessment and data collection. Moreover, important clinical domains including disease activity, skin disease activity and fatigue were not assessed which could significantly limit the proper description of the study cohort. Also, it is important to mention that gait variability was assessed over a 10-meter distance. Ideally, future studies should include longer distances while assessing this metric. Finally, the presence or absence of foot deformity were recorded in a qualitative manner (presence/absence). Using standardized tools such as the structural index could have been more relevant to ensure comparability between studies.

5. Conclusion:

Foot pain and disability have been reported to be important manifestations of PsA. This was confirmed in this study since severe levels of foot pain and related disability were reported despite the use of

DMARD/Biological therapy in more than eighty percent of the patients. Disability was further demonstrated through the objective assessment of foot function. The findings showed that STPs obtained from IMUs during a standardized 10-meter walk test were significantly altered and that there were strong correlations between pain, disability levels, and STPs. Besides, we demonstrated for the first time, increased gait variability in people with PsA which was not correlated with pain levels suggesting that instability during gait in PsA could be independent of foot pain and that it should be further assessed in larger studies. The findings of this study add important information on gait in people with PsA, a population for which research on gait and posture is scarce.

Abbreviations:

BMI: body mass index, CRP: c reactive protein; CV: coefficient of variation; DMARD: disease-modifying anti-rheumatic drugs; FFI: foot function index; GCT: gait cycle time; MCID: minimal clinically important difference; NRC: numerical rating scale; PsA: psoriatic arthritis; STPs: spatiotemporal parameters; 10MWT: 10-meter walk test.

Declarations:

Ethics approval and consent to participate

The study was approved by the CIUSSS de l'Estrie-CHUS Ethics Board (2019- 3182), and all the participants gave their informed consent to participate in the study.

Consent for publication

Not applicable

Availability of data and materials:

The dataset used and analyzed during the current study is available from walha.roua@usherbrooke.ca on reasonable request.

Competing interests

The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

Funding

This research was funded by The CANADIAN MSK REHAB RESEARCH NETWORK, CFI-148081.

Authors' contributions

RW and PB conceived the study. RW collected and analyzed the data and wrote the first full draft of the manuscript. PB assisted with the analysis of data. PB, PD and NG all reviewed the manuscript drafts. All authors read and approved the final manuscript.

Acknowledgment

Not applicable.

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Figures

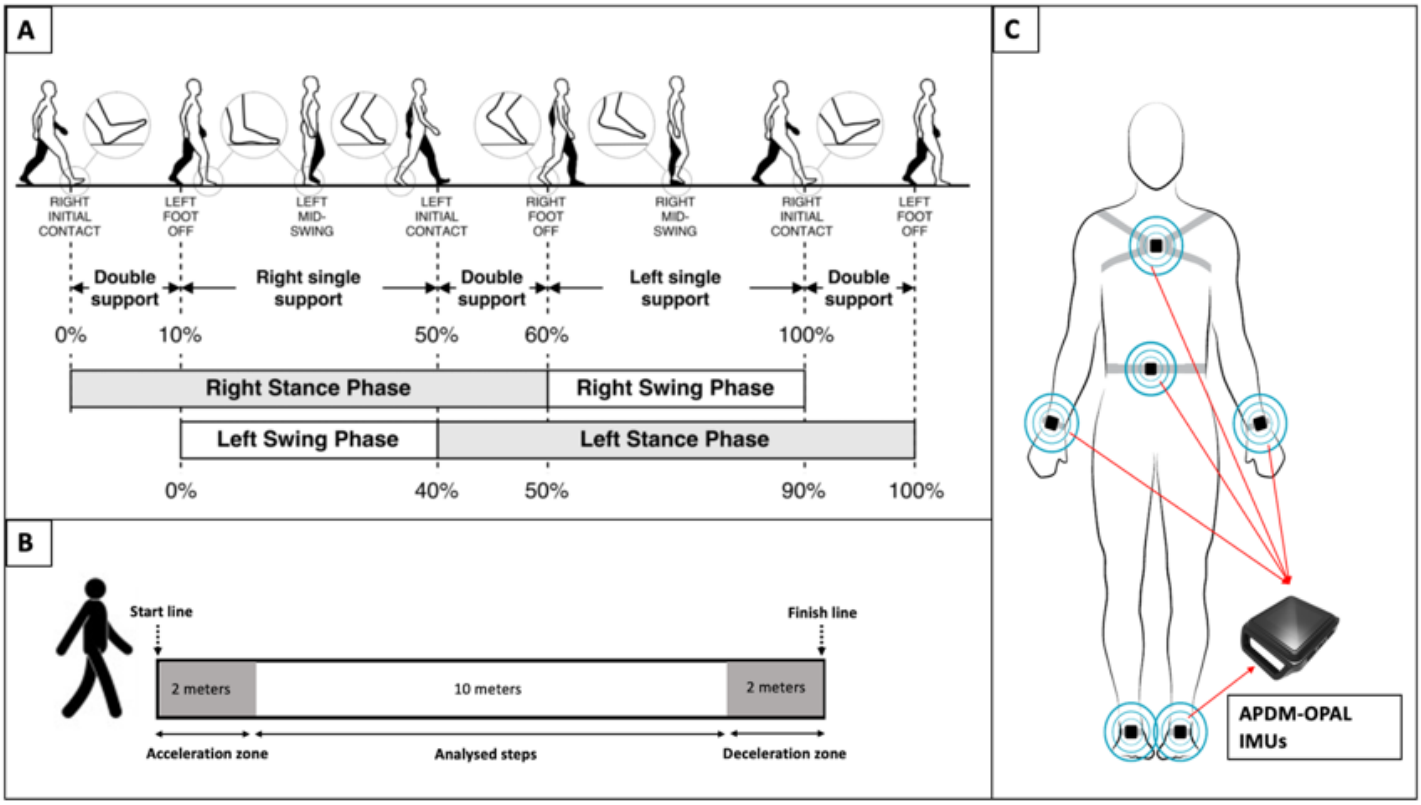

Figure 1

A : The gait cycle phases taken from an open access article [41]; B: 10 meters walk test (10MWT); C: The Mobility Lab sensors placement.

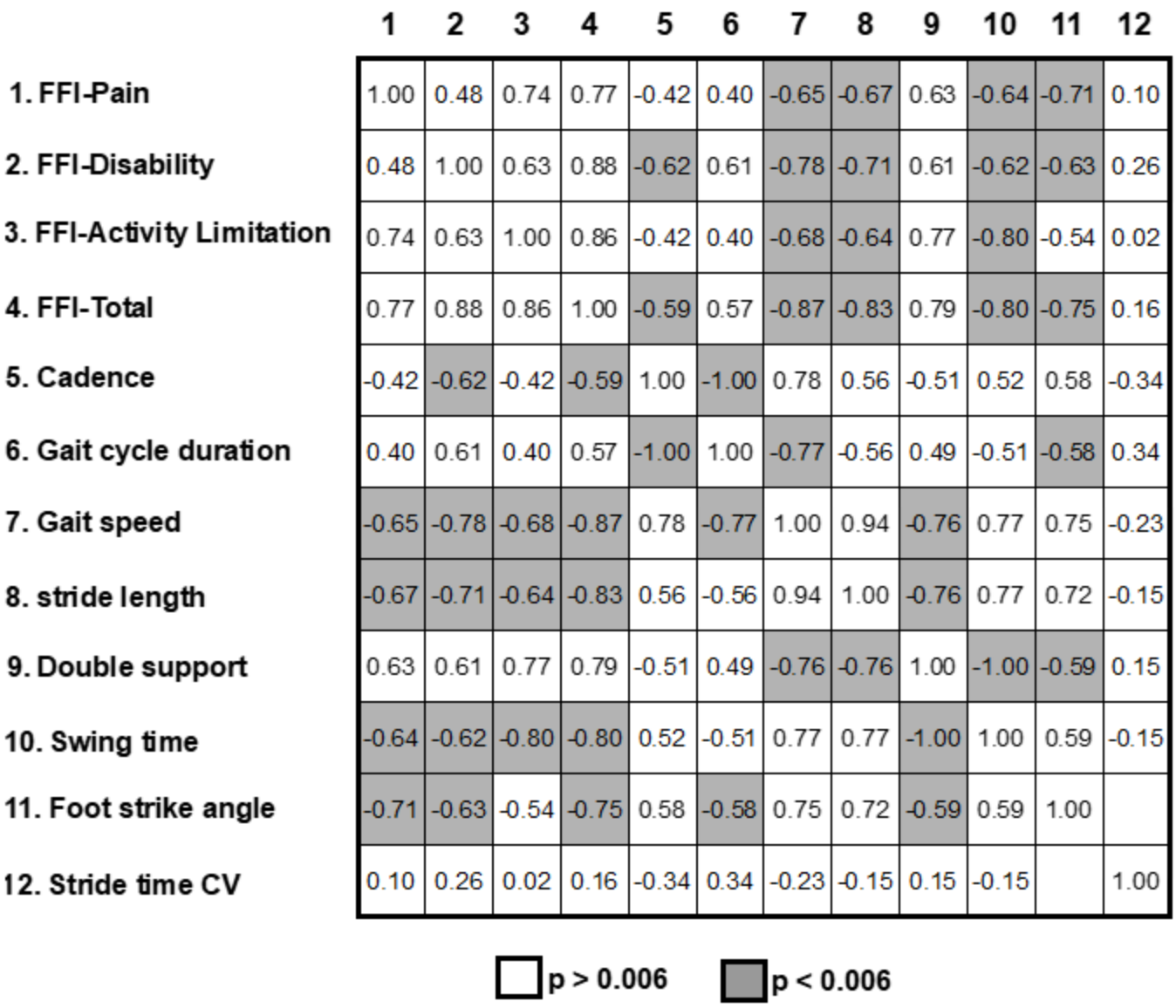

Figure 2

Correlation matrix of the relationships between spatiotemporal parameters, stride time variability and the foot function index

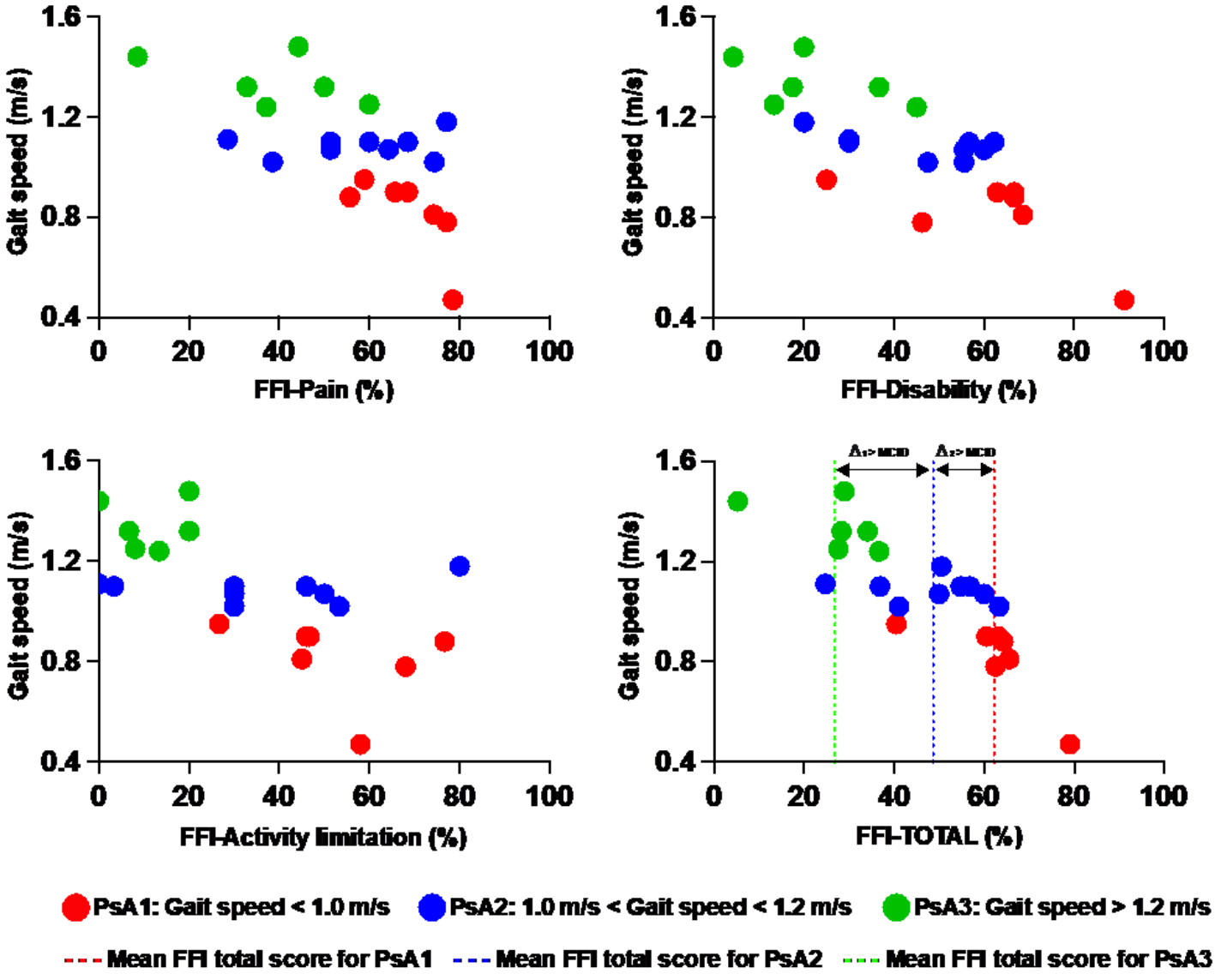

Figure 3

Scatter plots of the relationships between gait speed and the foot function index for PsA subgroups PsA1 Participants with gait speed below 1.0 m/s, PsA2 participants with gait speed comprised between 1.0 and 1.2 m/s and PsA3 participants with gait speed higher than 1.2 m/s, FFI Foot function index Δ1 Difference in the FFI total score between PsA2 and PsA3 Δ2 Difference in the FFI total score between PsA1 and PsA2