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Validation of the foot profile score

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ABSTRACT

Background: There are numerous static measures of foot posture but there is no published score of dynamic foot motion. Three-dimensional gait analysis can include a multi-segment foot model like the Oxford Foot Model (OFM) to comprehensively quantify foot kinematic deviations across the gait cycle but it lacks an overall score, like the Gait Profile score (GPS), used to summarize the quality of lower extremity motion.
Research question: This paper introduces the Foot Profile Score (FPS), a single number, analogous to the GPS but based on kinematic data of the OFM. The aim of this study is to validate the FPS by studying its properties and design, and analyse it against a clinical assessment of foot deformity.
Methods: Concurrent validity was established for the FPS analysing the relationship with Clinical Foot Deformity Score (CFDS) in 60 subjects with a condition affecting the lower limbs globally Content validity was established for the six Foot Variable Scores (FVS) that make up the FPS using a multiple regression of the CFDS on the 6 FVS in the 60 subjects. Predictive validity was established analysing the relationship of the FPS and GPS comparing 60 global involvement subjects with 60 subjects with isolated foot deformity.
Results: Pearson correlation between the FPS and CFDS was significant at 0.62 ($p < 0.001$). Each element of FVS contributes positively to predicting the CFDS with $R2 = 0.456$ ($p < 0.001$). FPS contributed independently to the prediction of CFDS ($t = 3.9$, $p < 0.001$). The correlation between the GPS and FPS in the global involvement group was significant at $r = 0.64$ ($p < 0.001$), while there was no correlation found with $r = 0.08$ ($p = 0.54$) in the foot deformity group.
Significance: The FPS is the first validated score of dynamic foot motion.

1. Introduction

Measuring foot deformity in a clinical or research setting has always been challenging due to numerous factors. Some available measures are condition specific, such as the Pirani Score for clubfoot [1] or measure only one element of a deformity, such as the Arch Height Index [2] or hindfoot valgus. A recent systematic review of the measurement of paediatric flat foot by Banwell and colleagues found four groupings of available assessments- plain film radiographs, foot print indices, static foot measures, and plantar pressure analysis [3]. The authors found that all groups were based on static analysis of foot postures. The authors concluded that dynamic measurement of foot motion is needed to improve our understanding of foot structure [3].

Three-dimensional (3D) gait analysis is a tool to measure dynamic motion in the lower limbs. It is widely used to identify deformity in a variety of conditions including osteoarthritis [4], clubfoot [5] and cerebral palsy [6] to assist in treatment planning. Traditionally the foot has been represented as a single rigid segment with just two degrees of freedom. More recently, 3D multi-segment foot models have been developed to improve our understanding of foot motion during gait.

The Oxford Foot Model (OFM) was developed as a multi-segment, 3D kinematic model that assesses dynamic motion of the foot [7]. It was developed to measure tibia, hindfoot, forefoot, and hallux motion in a clinical setting. It can identify the presence of deformity compared to a healthy population, monitor change of foot posture over time, and measure change in ankle and foot motion before and after intervention [7]. Published literature confirms the OFM is being used clinically and in research settings world-wide to evaluate populations with foot deformity [8–11]. The OFM has been shown to be repeatable in healthy populations (adults and children) for both intra-tester and inter-tester

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repeatability [7,12,13]; and children with foot deformity including clubfoot and cerebral palsy [14]. The OFM is a comprehensive measure of foot/ ankle motion with each segment being measured in 3D. With the large amount of data available, it can be difficult to quantify as an outcome measure. Therefore, an overall score of foot motion using the kinematic data from the OFM would be beneficial.

The Gait Profile Score (GPS) was developed to provide a single measurement of the quality of an individual's gait pattern based on lower limb kinematics [15]. The GPS is calculated as the root mean square average of 9 key kinematic variable scores (Gait Variable Scores-GVS), each calculated as the root mean square difference between a patient's data and normative data for both legs [15]. Since its creation, the GPS has been widely used in clinical and research settings. However, the GPS includes the traditional measurement of the foot as a single segment. An additional score representing detailed foot and ankle motion may therefore be beneficial, particularly in patients with foot deformity as the predominant pathology.

This paper introduces the Foot Profile Score (FPS), a single measurement of dynamic foot motion, constructed similarly to the GPS, but based on OFM kinematics. The aim of this study is to validate the FPS by evaluating its inherent properties and design, and analyse it against a global clinical assessment of foot deformity.

2. Methods

2.1. Construction of the foot variable scores, the foot profile score, and the foot movement analysis profile

The Foot Variable Scores (FVS), the Foot Profile Score (FPS), and the Foot Movement Analysis Profile (F-MAP) were calculated using the same formula as the construction of the GPS [15] but using 6 key kinematic variables from the Oxford Foot Model for both the right and left legs.

Thus if $x_{i,t}$ is the value of foot variable *i* calculated at a specific point in the gait cycle *t*, and $\bar{x}_{i,t}^{ref}$ is the mean value of that variable at the same point in the gait cycle for the reference population then the i^{th} foot variable score (FVS) is given by:

$$FVS_i = \sqrt{\frac{1}{T}\sum_{t=1}^{T}(x_{i,t} - \bar{x}_{i,t}^{ref})^2}$$

where *T* is the number of instants into which the gait cycle has been divided. The FPS is then the RMS average of the FVS variables:

$$FPS = \sqrt{\frac{1}{N}\sum_{i=1}^{N} FVS_i^2}$$

where *N* is the number of FVS variables used, in this case 6 (hind foot dorsiflexion, forefoot dorsiflexion, hind foot inversion, forefoot supination, hind foot rotation, forefoot adduction)

The 6 FVS represent the motion of the hindfoot relative to the tibia in the sagittal, coronal and transverse planes, as well as the motion of the forefoot relative to the hindfoot in the sagittal, coronal and transverse planes. The more the foot deviates from the reference data, the higher the FPS. The FVS and the FPS do not reflect the direction of the deviation (e.g. plantarflexion or dorsiflexion). The F-MAP is a bar chart of the 6 FVS for each foot and the FPS to provide a visual representation of where a subject deviates from the normative data (Fig. 1).

2.2. Validation of the foot profile score

As with the GPS, the FPS already has high face validity as it is based on the kinematic data of the OFM. The repeatability of the FPS is also inherent as the marker placement of the OFM has been extensively studied with good results [7,12–14]. Therefore, the formal validation process included analysing concurrent validity, content validity, and predictive validity.

2.2.1. Concurrent validity

There is no published dynamic foot deformity scale to which it is appropriate to correlate the FPS [3]. In the absence of this- we created a clinical rating scale of foot deformity to use in the validation process. We sent sagittal and coronal close-up foot videos of 60 subjects to 10 gait analysts affiliated with a 3D gait laboratory from 4 countries (5 physiotherapists, 2 orthopaedic surgeons, 2 clinical scientists/ engineers and 1 paediatric physiatrist). Each subject was scored by 5 gait analysts. The subjects included a range of demographics and severity of foot deformity. We made sure to represent the full range of deformities, varying from planovalgus to cavo-varus foot deformities. There were 30 children and 30 adults; 36 males and 24 females. 23 Subjects had orthopaedic diagnoses, 21 had cerebral palsy and 16 had neurological diagnoses. For each of the 60 subjects, the gait analysts scored both feet separately. We used right leg data in 31 subjects/ and left leg data in 29 subjects. There were no markers on the feet in the videos. We asked the gait analysts to rate the overall appearance of the foot using a scale from 0 to 3, which we termed the Clinical Foot Deformity Scale (CFDS: 0 = normal, 1 = mild, 2 = moderate, 3 = severe foot deformity) with no further instructions. All 60 subjects had OFM kinematics [7] collected using a Vicon T-series motion capture system (Vicon Motion Systems Ltd.) including 16 cameras collecting at 100 Hz. Subjects walked at self-selected speed over level ground for both the video and motion capture trials.

The CFDS was taken as the mean of all 5 gait analysts' ratings for each subject. The FPS was calculated for the same leg as used for the CFDS scoring for each subject. Pearson correlation coefficient was used to analyse the relationship between FPS and CFDS as a measure of concurrent validity.

We hypothesised that FPS would correlate moderately with CFDS as FPS also contains transverse plane information not easily visible in a clinical assessment.

2.2.2. Content validity

To analyse the FVS (sagittal plane- hindfoot dorsiflexion and forefoot dorsiflexion; coronal plane– hindfoot inversion and forefoot supination; transverse plane– hindfoot internal rotation and forefoot adduction) - we looked at a multiple regression of the CFDS on the 6 FVS for the above mentioned 60 subjects.

We hypothesised that the 6 FVS chosen would contribute positively to CFDS.

2.2.3. Predictive validity

We analysed the relationship between FPS and GPS to evaluate if the measurement of foot deviation during gait provides additional information to the measurement of the overall gait pattern. We collected 2 groups for the analysis: the above mentioned 60 subjects who had predominantly global involvement (deviations at more than one joint including proximal involvement) and a group with isolated foot deformity. The foot deformity group consisted of children with clubfoot aged 5–16 (mean 10 years), with 45 males/ 15 females and 39 right legs/ 21 left legs analysed. For children with bilateral clubfoot we analysed their more involved foot (the foot with the higher FPS). All subjects had a conventional lower limb model [28] and OFM kinematics collected using a 16 camera Vicon T-series motion capture system (Vicon Motion Systems Ltd.). GPS and FPS were calculated for both groups. Pearson correlation coefficient was used to analyse the relationship between bilateral GPS and unilateral FPS, using the leg with the highest FPS for consistency purposes for both groups.

Additionally, to consider the correlation coefficients in the groups, we also report the ratio of the variances for FPS and GPS. As GPS and FPS are likely to be correlated, 95% confidence intervals for the ratio in each population can be calculated using a method based on the Pitman-Morgan test [16,17] illustrated by Snedecor and Cochran [18].

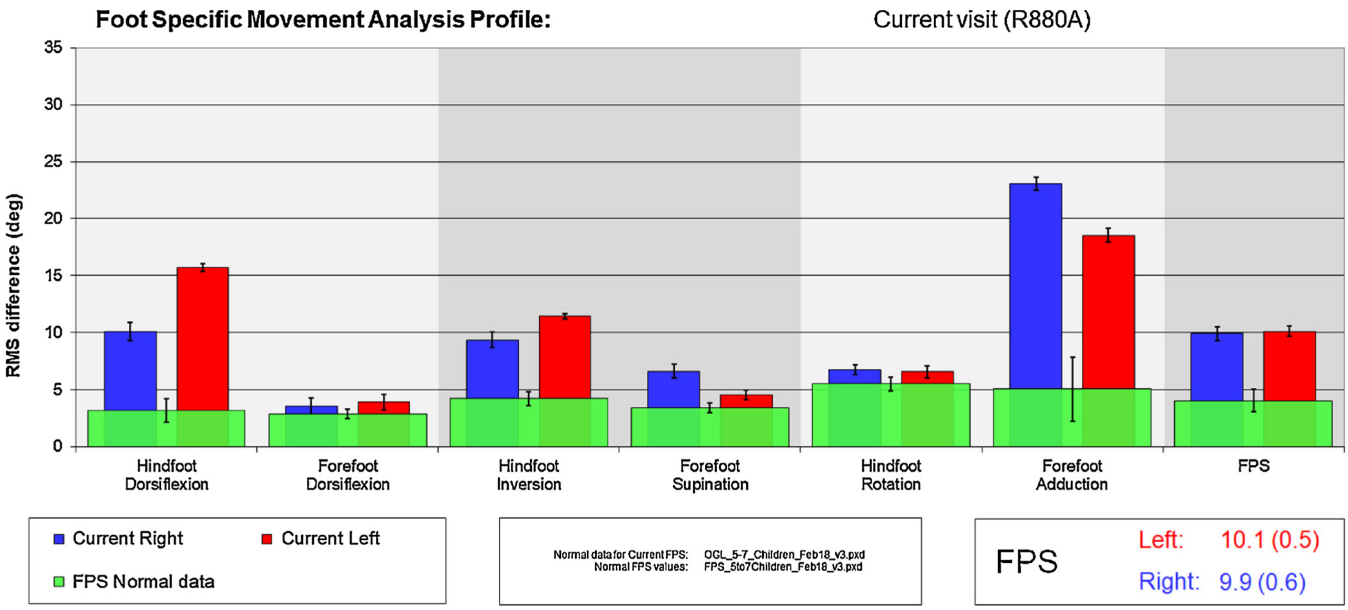

Fig. 1. An example of a Foot Movement Analysis Profile (F-MAP).

We hypothesised that FPS will give new information not offered by GPS and therefore the correlation of GPS and FPS will be higher in the global involvement group than the foot deformity group. Additionally, the ratio of variances (FPS:GPS) should be higher in the foot deformity group than the global involvement group.

3. Results

3.1. Concurrent validity

The mean CFDS scores for each pathological group were cerebral palsy 1.5 (SD 1.0), orthopaedic 1.1 (SD 1.1) and neurological 1.9 (SD 1.0) indicating a range of deformity within each group, and the amount of deformity was consistent across groups. The mean FPS score for all 60 subjects was 9.8 ° (SD 3.6) indicating a range of deformity within the group (normal FPS is 4.5 ° (SD 0.9). The Pearson correlation between FPS and CFDS was significant at 0.62 with $p < 0.001$ (Fig. 2).

3.2. Content validity

Table 1 shows the multiple regression of CFDS on the 6 component scores of the FPS. For comparison, the corresponding regression with identical coefficients for each component has a coefficient of 0.033 (SE 0.005). Thus, although they differ in individual statistical significance, we see that the regression coefficients in Table 1 are all within one standard error of the combined regression coefficient. Furthermore, the residual standard deviation is marginally smaller when using identical coefficients than using six independent coefficients. This is confirmed using analysis of variance where the reduction in the sum of squares from fitting 5 additional coefficients is non-significant ($F_{5,53} = 0.34$, $p = 0.89$). This confirms that assigning equal weight to each constituent component of the FPS performs better than a model with separate weights for each constituent component and that each component is contributing positively to predicting the clinical scores.

We have already shown the significant correlation between CFDS and FPS, but due to the way the GPS is constructed, we note there is also a significant correlation of CFDS with GPS ($r = 0.60$, $p < 0.001$). It is therefore necessary to show that the association between FPS and CFDS is not a simple consequence of the mutual association with GPS. Table 2 shows that, when analyzing the regression of the CFDS on the GPS and FPS, the FPS is contributing independently to the prediction of the CFDS, ($t = 3.9$, $p < 0.001$).

3.3. Predictive validity

The global involvement group had a mean GPS of 10.3 ° (SD 4.0) and a mean FPS of 11.1 ° (SD 3.2) indicating that at group level both distal and proximal joints contributed to gait abnormalities. The foot deformity group had a mean GPS of 6.6 (SD 1.6) and a mean FPS of 9.2 (SD 3.4) indicating foot specific problems in this group. The Pearson correlation between GPS and FPS in the global involvement group was significant at $r = 0.64$ with $p < 0.001$ (Fig. 3). No significant correlation was found between GPS and FPS in the foot deformity group at $r = 0.08$ with $p = 0.54$ (Fig. 4).

The ratio of the variances for FPS and GPS in the global involvement group was 0.64 (95% CI 0.43, 0.97), while in the foot deformity group it was 4.55 (95% CI 3.78, 7.64). With a wide difference between their confidence intervals, predictive validity of the FPS was established.

4. Discussion

This paper introduces the Foot Profile Score- a measurement tool aiming to represent dynamic foot motion as a single meaningful numerical value.

Through our validation process we have proven our stated hypotheses were true. The FPS showed good correlation with CFDS and all of the 6 FVS contributed positively to the prediction of CFDS. The FPS does offer different information than GPS, especially in populations where foot deformity is dominant.

Due to the lack of an available dynamic measure to validate the FPS against, we created the Clinical Foot Deformity Score. The CFDS expresses expert opinion and is based on a visual impression of foot deformity that clinicians use in their daily practice. It is encouraging the FPS correlates well with the mean CFDS, scored by 5 experts. We wouldn't expect a perfect correlation as the FPS gives quantitative information on all three planes of movement; in particular the transverse plane which is difficult to evaluate clinically or with 2D video.

The regression of CDFS on the 6 FVS shows that each of the score components contributes positively to predicting the clinical scores. It also reaffirms that all 6 kinematic variables are appropriate to include in the FPS, with equal weights. Due to the limited sample size and high levels of correlation of the individual components of the FPS, it is

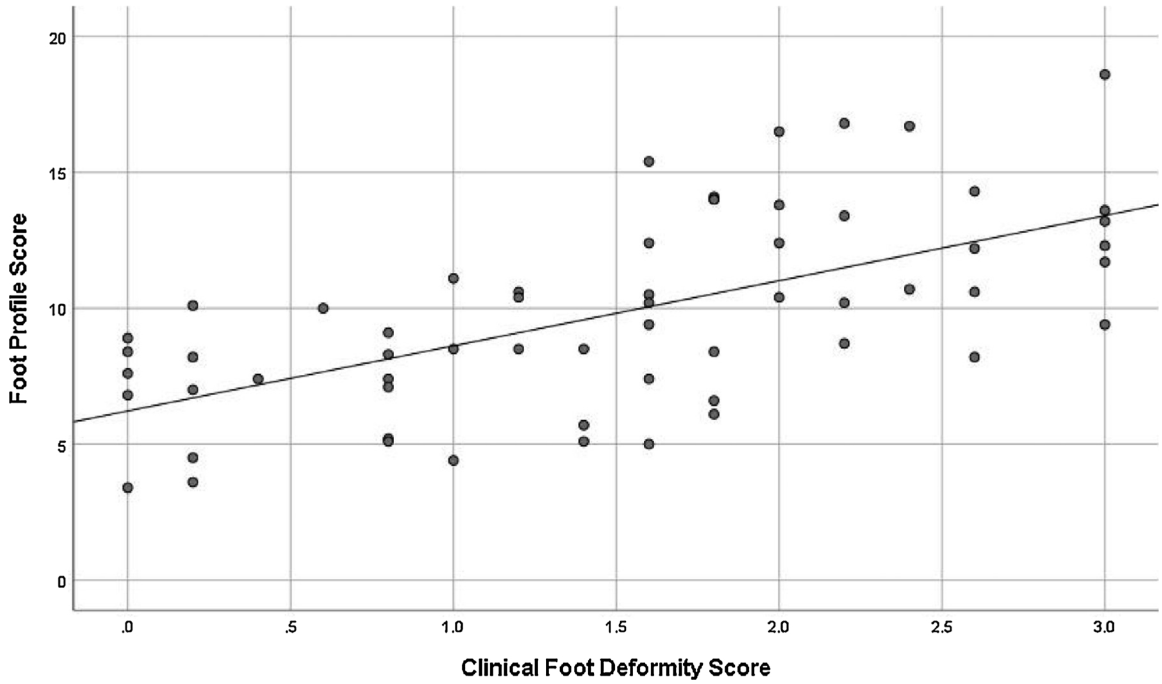

Fig. 2. Scatterplot of the Foot Profile Score and the Clinical Foot Deformity Score.

Table 1
Regression of the CFDS on the 6 component scores of the FPS (R2 = 0.456 ($p < 0.001$)).

	Regression Coefficient	Standard Error	p
(Constant)	*−0.099*	*0.301*	
Hindfoot sagittal	0.040	0.016	0.014
Forefoot sagittal	0.033	0.029	0.255
Hindfoot coronal	0.052	0.021	0.019
Forefoot coronal	0.019	0.026	0.462
Hindfoot transverse	0.019	0.021	0.377
Forefoot Transverse	0.024	0.014	0.095

Table 2
Regression of the CFDS on the FPS and GPS.

	Regression Coefficient	Standard Error	t	P
(Constant)	*−0.505*	*0.279*		
GPS	0.091	0.025	3.7	0.001
FPS	0.108	0.028	3.9	< 0.001

unsurprising that several of the FVS did not reach statistical significance. However, the FPS produced a better fit to the CFDS than the model with separate components. The positive and substantial contribution of FVS in predicting the CFDS is indicative of the content validity of FPS.

The fact that GPS also correlates to CFDS isn't surprising as GPS does model the foot crudely as a single rigid segment calculating ankle dorsiflexion, foot adduction and foot progression. In addition if severe foot deformity is present, this can induce compensations at more proximal joints (hip and knee) which will influence the GPS. This is why we felt it important to include the regression of the CFDS on GPS and FPS (Table 2) proving FPS contributed independently of the GPS to the prediction of the CFDS.

A strong case for FPS validity is that a moderate correlation between FPS and GPS was found in the global involvement group but no correlation was found in the foot deformity group. This indicates that whilst FPS represents gait deviations not reflected by GPS in both groups, the FPS provides completely new information in individuals where foot deformity is dominant. We also reported a more powerful approach to analyzing predictive validity of FPS that we believe to be new. When considering the ratio of the variances for FPS and GPS, we found the ratio to be increased in the foot deformity group compared to the global involvement group. This is because FPS should be sensitive in identifying differences between patients whose underlying problem is related directly to their feet, compared to differences in their GPS.

In patients with an isolated foot condition with little effect on proximal joints the GPS would be relatively unaffected. This reinforces the need for a separate foot specific outcome measure. A combination of GPS and FPS may be appropriate to report in these situations to more meaningfully describe an individual's gait pattern. A future consideration could be to remove the conventional lower limb model ankle kinematics from the GPS calculation when GPS and FPS are reported together.

Since its introduction in 2009, the Gait Profile Score has been used in clinical practice world-wide, particularly in children with cerebral palsy to improve understanding of their complex gait patterns [19], evaluate the use of Botulinum toxin [20] and evaluate surgical outcomes [21]. In addition to cerebral palsy, there is published research using GPS in other populations such as Charcot-Marie Tooth [22], Hereditary Spastic Paraplegia [23], Multiple Sclerosis [24], Parkinson's Disease [25], and amputees [26]. The GPS has also been used to create or validate other outcome measures [27,28].

We envision the Foot Profile Score will be used similarly to GPS, to quantify foot specific deformity during gait in a wide range of populations, and demonstrate the outcome of intervention strategies. These may include conditions with global involvement and progressive foot deformity, such as cerebral palsy and stroke. Moreover, the FPS would be a useful clinical and research outcome measure in foot-specific conditions that affect dynamic foot motion and gait, such as pes cavus or flat foot.

5. Study Limitations

A limitation of this study is that we have only considered the OFM to create the FPS. It is unclear how it would work with other foot models, but theoretically it could be applied in a similar way. As with any summary gait index, there is a trade-off between simplicity and

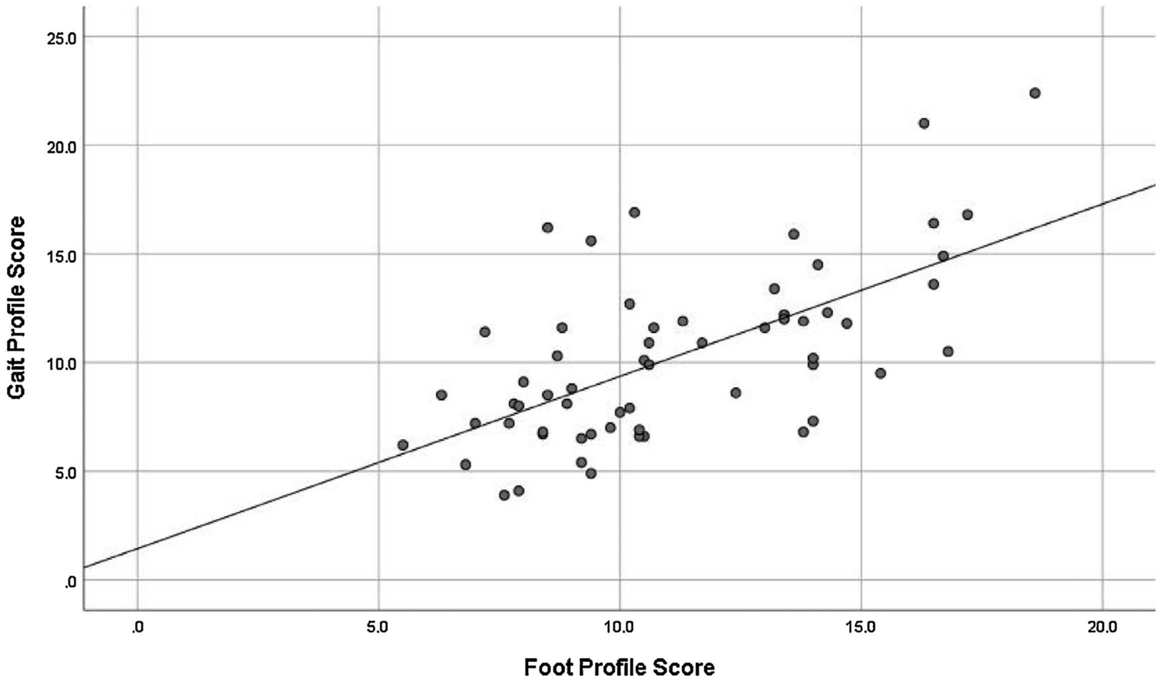

Fig. 3. Global involvement group: scatterplot of GPS (bilateral) and FPS (unilateral).

information content, therefore we still recommend the FPS is used in conjunction with the full kinematic data.

Hallux motion is not included in the FPS due to numerous factors. The hallux is a short segment measured with 2 markers in 2D. During a clinical session of 3D gait analysis it also has a high tendency to get knocked and replaced during pathological gait, making it less reliable than the other segments. Further study into how the addition of the hallux influences the overall FPS would be beneficial.

A second consideration for future work is to represent the FVS as a positive or negative value depending on the direction of deviation from the normative data. This may be particularly interesting when analysing foot motion over time or pre/post a surgical intervention as it is possible for an overall FPS to remain abnormal- but the foot posture to have changed (for example from equino-varus to excessive dorsiflexion with hindfoot valgus).

The FPS was specifically designed to offer a dynamic score of foot motion. Our previous work has shown that standing foot posture does not necessarily correlate to dynamic foot movement [29], therefore further work could be done to understand the differences of static foot mal-alignment versus abnormal dynamic foot motion. A method that could be applied to evaluate this has recently been suggested [30].

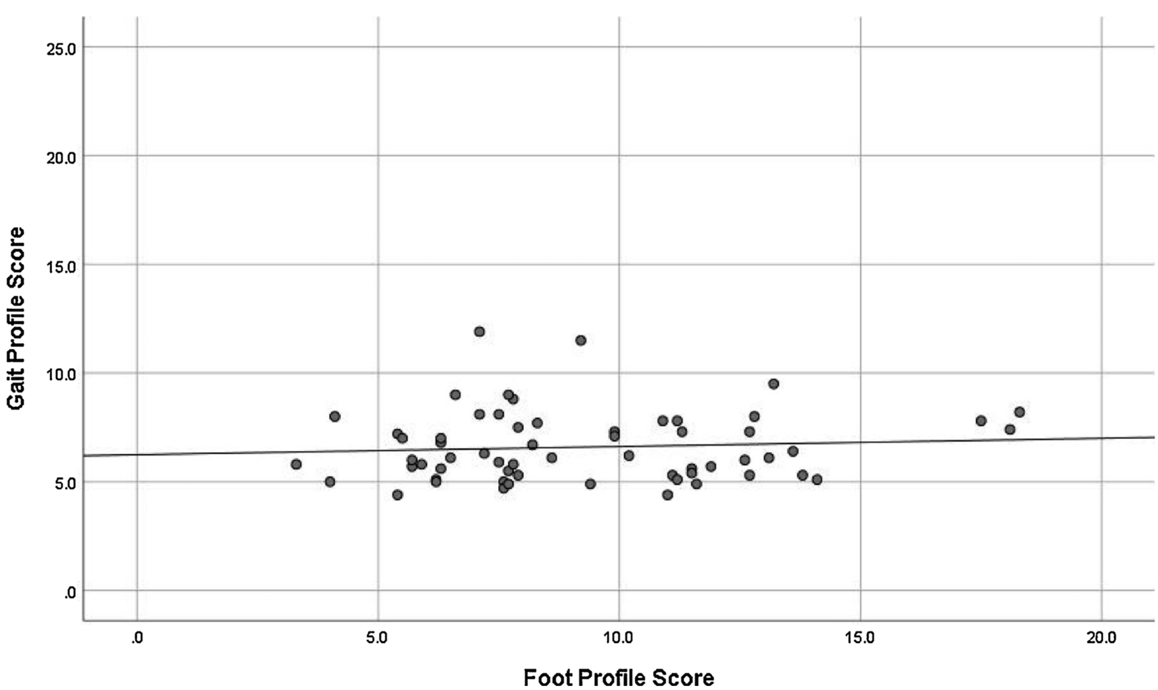

Fig. 4. Foot deformity group: scatterplot of GPS (bilateral) and FPS (unilateral).

6. Conclusions

This study successfully validated the Foot Profile Score by studying its inherent properties and design, and by analysing it against a global clinical assessment of foot deformity.

The FPS is the first validated outcome measure of dynamic foot motion. It is a single measurement based on OFM kinematics. The FPS gives additional information to GPS, and should be presented alongside other gait data to offer a better understanding of an individual's gait deviations.

The FPS has the potential to assist clinicians and researchers in quantifying foot abnormalities during gait, to monitor change over time, and to measure the outcome of intervention.

Conflicts of interest

None

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