The effect of tuning ankle foot orthoses-footwear combinations on gait kinematics of children with cerebral palsy: a case series

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Abstract

Study Design: Case series

Background: AFOs are a commonly prescribed medical device given to children with cerebral palsy (CP) in an attempt to improve their gait. The current literature is equivocal on the effects AFOs have on the gait of children with CP. The vast majority of AFOs issued are not subject to AFO-FC tuning. There are emerging studies investigating the effects tuning AFO-FCs has on the gait of children with CP. However, the research is limited, and there is a lack of quantitative data.

Objective: To compare the kinematics of tuned versus non-tuned gait in children with CP.

Methods: Gait analysis assessment of five children aged between 7-11 years with a diagnosis of CP (one hemiplegic and four diplegic participants, two female, three male, with a Gross Motor Functional Classification System (GMFCS) of 2) at a Gait Analysis Laboratory.

Results: In comparison to barefoot and non-tuned gait, walking with a tuned AFO-FC produced improvements in several key gait parameters. Including hip flexion and extension, posterior pelvic tilt and knee extension. Results also indicated that the type of gait pattern demonstrated by the participant affected the outcomes of tuning.

Conclusions: Tuning the AFO-FC of children with CP has the potential to improve hip function, pelvic function, knee extension in stance phase and knee flexion during swing phase and that an non-tuned AFO-FC can potentially decrease hip function, posterior pelvic tilt and increase knee extension.

Clinical Relevance: Whilst AFO-FC tuning has been recommended for routine clinical practice, there still remains a paucity of research on the kinematic effects of using a tuned AFO-FC compared to a non-tuned. This paper provides a comparison of kinematics on children with CP, during barefoot, non-tuned and tuned AFO-FC walking with a view to inform clinical practice.

Key words: Cerebral Palsy, Orthotic Devices. Ankle foot orthosis, AFO, Kinematics, Gait analysis; Children; Assistive Technology

Introduction

Cerebral palsy (CP) is a non-progressive disorder although the effects of growth predispose children with CP to the secondary problems of muscle contractures, bony deformities, and pathological gait(1). Such pathologies often require an ankle foot orthosis (AFO) intervention(2). Although the provision of an AFO is a commonly prescribed intervention for this patient group(3–5) rigorous evidence of their efficacy is limited(5–10). Despite the International Standards Organisation (ISO) emphasising that an orthosis has the potential to change the musculoskeletal and neuromuscular system(11).

CP gait has been classified and documented previously (12–17). Patients with pathological gait have abnormal lower limb kinematics, particularly at the shank segment. Attempting to normalise the shank kinematics offers a higher chance of optimum thigh and trunk kinematics and knee and hip kinetics(18–20).

AFOs are commonly prescribed in an attempt to manipulate the ground reaction force (GRF) and normalise gait kinetics and kinematics. Research has demonstrated the effect AFOs have on the GRF during the stance phase of gait(4,18,21–30). The available research on the efficacy of AFOs is equivocal (21,22,31–36); the lack of consensus within the literature may be due to the heterogeneous nature of CP, with studies grouping together the results of differing presentations of CP. Other factors include comparing different AFOs against each other, a lack of detail regarding the AFO intervention used, a lack of clinical justification for the AFO prescription and a lack of detail regarding the physical presentation of the participants being studied(37).

Previous studies have also reported mean results across groups of children with CP which may skew the results and misinform practice. A more personalised case study approach has been advocated when researching children with CP(38). A lack of ankle-foot orthosis footwear combination (AFO-FC) tuning within the studies may also be a factor in the ambiguity of reported results.

AFO-FC tuning and biomechanical optimisation have been inter-relatable terms, although their meaning differs and has been defined(39,40). Tuning can be defined as the process whereby fine adjustments are made to the design of the AFO-FC to optimise its performance during a particular activity(18,41). It involves the manipulation of the shank to vertical angle (SVA) by altering the heel sole differential via the addition of wedges to the footwear to optimise the entry and exit from mid-stance and influence the GRF in the sagittal plane(18,42). The SVA can be defined as the angle of the shank relative to the vertical, measured in the sagittal plane in degrees(18).

Detailed information on the tuning process has been documented(18,42,43). Owen(18,44) indicates that anthropometric measures dictate that a SVA of 10-12° inclined from the vertical brings the knee joint centre over the middle of the foot during temporal mid-stance (TMST), as defined by Gibson et al(45), in non-pathological individuals. Of the five pre-requisites for non-pathological gait(17) it is stability which also contributes to the other four factors(46). It is the importance of stability which highlights TMST as being a crucial aspect of the gait cycle. The inclination of the shank allows the forward translation of the head, arms, trunk, and pelvis(46). In contrast, with a vertical SVA this is not possible, unless the knee hyperextends, which is not desirable. The optimum inclination of the SVA also allows the centre of pressure to remain within the base of support, which allows switching between external flexing and extending moments during gait. This creates stability through the positioning of the centre of mass and the centre of pressure, which dictates the position of the GRF(46). Tuning has been recommended for children with CP(6), however, quantitative data on the effects of tuned AFO-FCs is scarce, research which is available has reported positive results(47–50).

The aim of the study was to use a case series approach to compare the sagittal plane kinematics and temporal-spatial parameters of each participant in non-tuned and tuned AFO-FC conditions, on the limb which is predominantly affected and on which they wear an AFO. Barefoot data is used as baseline data for the participants gait without orthotic intervention. A case series analysis approach was chosen based on the underlying premise that identification of the sources of individual variation in treatment responses is a critical next step towards advancing evidence-based practice in rehabilitation for children with CP(38), rather than the use of mean group differences which does not imply that this intervention was effective for each study participant or ensure positive outcomes for all with CP(38).

Clinical interpretation of instrumented gait analysis first identifies how the participant differs from non-pathological gait and then the likely cause of the deviation. However, it is important to recognise that kinematic deviations are not bijective and thus the same impairment may result in a range of kinematic deviations(51).

Methods

Participants

Five children (two female and three male) aged 7-11 years with a diagnosis of spastic CP and a Gross Motor Functional Classification System (GMFCS) of two, as determined by an experienced paediatric physiotherapist, took part in this study. None of the participants required any form of mobility device to aid walking. All participants were long-term solid AFO users (long-term was defined as having worn a solid AFO for five years or more). Solid AFO in this study means the AFO blocked ankle movement in all three planes and did not deform during stance. See Table 1 for participant anthropometrics and AFO design information. Gender was not considered in the recruitment process.

INCLUSION CRITERIA

- Independent ambulators.
- The participant must already wear either unilateral or bilateral AFOs; there is no time limit on how long they have been wearing AFOs.
- The participant must be deemed to be GMFCS one or two.
- Aged between 5 – 11 years old.
- Informed consent received.

EXCLUSION CRITERIA

- Excessive contractures at the hip or knee (more than 25°).
- Excessively exaggerated stretch reflex.
- Excessive foot progression angle.
- Any orthopaedic surgery or medical intervention in the last six months which may influence mobility.
- Planned surgery.

Ethical approval

This study was granted ethical approval by the National Research Ethics Service (NRES), Ethics Committee [redacted] Research and Development Directorate [redacted] and a local University Ethics Committee. Parents/guardians provided written informed consent and the child's verbal assent was confirmed prior to inclusion in the study.

Testing procedure

All participants underwent a full lower limb physical assessment with an experienced orthotist and paediatric physiotherapist (See supplementary material for physical assessment data). Following this, the children who met the inclusion criteria had their gait assessed in clinic by an experienced orthotist and were then cast for an AFO (see Table 1 for individual participant AFO prescriptions) based on their individual clinical needs. Participants attended the orthotic clinic approximately three weeks after casting, to have their AFO/s fitted by the same orthotist. Participants were issued with their non-tuned AFO-FC and footwear three weeks before testing commenced, to enable acclimatisation. All participants were issued with the same over splint footwear in either black or white (Blacky style; Schein Orthopädie Service KG, Germany), which had a heel sole differential of 8mm before any adaptations were added.

Retro-reflective markers were then placed on the lower limbs, to capture kinematics of gait. For this study, the Plug-in-Gait (P.I.G) model (58,59), which is a modified version of the Helen Hayes model(58,60), was used for the lower limbs.

P.I.G, is used by a vast majority of gait laboratories(52) and has demonstrated reliability of kinematic data, suggesting that the magnitude of the errors obtained using this model are clinically reasonable(53).

Testing took place over two days, three weeks apart at the [redacted]University gait laboratory. The area was a dedicated thermostatically controlled gait laboratory with a figure of 8-track to ensure walking was continuous with no abrupt turns. The walkway measured 30.5 metres in length. Its design also precluded bias to the same leg on corners by balancing the number of left and right turns. Two sets of timing gates were set up on the walkway to measure the participant's speed.

Following a standardised habituation period, which included familiarisation with the walking track and the laboratory in general, testing began. Participants were asked to walk at a self-selected speed for 3 x 4-minute trials, the researcher walked alongside the participant holding a portable gas analysing system which formed part of another study(50). Day one consisted of testing of the barefoot and non-tuned AFO-FC conditions. The order of testing for barefoot and non-tuned conditions were randomised. There was a 60-minute rest period between conditions.

At the end of this testing period each participant had their AFO-FC tuned by an experienced orthotist, using 2D video vector analysis, to establish the optimum SVA. The tuning process followed Owen's(42) algorithm. Non-tuned in this study means the AFO-FC was not set to an optimum SVA and the footwear was not adapted to optimise entry and exit from mid-stance. However, it was deemed unethical to supply the participants with an AFO which did not have the correct angle of the ankle in the AFO (AAAFO) to represent the length of gastrocnemius, as doing so may have caused the participant pain and put them at risk of a pressure sore. Temporary wedges and where necessary point loading rockers (PLR), were added to the sole of the footwear via masking tape until the optimum SVA was determined. (See figure 1a for an example of a temporarily tuned AFO-FC).

Once the SVA was determined, the footwear was then sent for permanent modification (see figure 1b) and was returned to the participants within five days. Participants were given the tuned AFO-FC to take home and acclimatise to, for three weeks before testing day two. Day two consisted of testing of the tuned condition which followed the same protocol as the barefoot and non-tuned conditions.

Data acquisition

Data were recorded using two force plates (AMTI OPT464508HF sampling at 1000Hz; AMTI, USA), 18 camera optoelectronic motion analysis system (sampling at 100Hz; Vicon, OMG, Oxford, U.K), and timing gates.

Data processing

Data were digitised and labelled using Vicon Nexus (version 2.5, Vicon, OMG, UK) and exported to Visual 3D (C-motion, Germantown USA) for analysis. Marker trajectory data were filtered using Vicon Nexus with a Butterworth 4th order zero-lag dual-pass, low pass filter with a cut-off frequency of 6Hz, which is typically used for walking data(54).

Five complete gait cycles were identified for analysis for each participant, in each of the three conditions. Descriptive statistics were calculated for temporal-spatial gait parameters and for pelvis, hip and knee kinematics in the sagittal plane. Speed and distance were calculated as an average of the 3 x 4-minute trials. Inferential statistics cannot be used as the sample size is less than 10; therefore, descriptive statistics will be used due to the heterogeneity of children with CP. In this paper the gait cycle will be described using the Ranchos Los Amigos terminology(55).

Reference data

The results were compared with a database of non-pathological children(56) with a change in a parameter towards non-pathological considered an improvement; and the opposite a deterioration. This reference data is in routine use at Gillette Children's Specialty Healthcare. The reference data were created using data from 81 patients, with an age range between 4 and 17 years, at one centre. All data were collected at self-selected walking speed, with a Vicon kinematic measuring system (Oxford, U.K) and AMTI force plates (Watertown, MA, USA). Data were sampled to 51 values during the gait cycle(56). This data set has been shown to have a high degree of consistency when compared to another highly regarded gait analysis service(56).

Results

Kinematic data for each participant is presented in Figures 2 and 3 with additional data available as supplementary material. The results of this study show that for case study one, all kinematic parameters were improved closer to non-pathological in the tuned condition when compared with non-tuned, with the exception of knee flexion at initial contact and peak knee flexion in stance. Knee flexion at TMST and peak knee extension changed from being outside of non-pathological values to within, in the tuned AFO-FC compared with barefoot. Crucially, the non-tuned condition resulted in an increase in peak knee extension compared to no intervention at all (barefoot).

For case study two, pelvic and hip kinematics all improved closer to non-pathological values in the tuned condition, with peak anterior pelvic tilt, peak posterior pelvic tilt, peak hip flexion and peak hip flexion in stance all improving to within non-pathological parameters. Conversely, the non-tuned AFO-FC caused peak anterior pelvic tilt, peak hip flexion and peak hip flexion in stance to move further outside of non-pathological values, compared to barefoot data.

Case study three's results indicated an improvement in pelvic and hip kinematics on both left and right limbs, compared to the non-tuned condition. Similarly, case study four demonstrated improvements closer to non-pathological in their hip and pelvic kinematics in a tuned AFO-FC with the exception of peak anterior pelvic tilt and peak hip extension. Although, both values were still within non-pathological parameters. There were also improvements in knee flexion at initial contact, knee flexion at TMST and peak knee extension, compared to non-tuned.

Case study five showed improvement in, peak hip flexion in stance, peak hip flexion, peak knee extension and peak knee flexion compared to both barefoot and non-tuned data. Peak anterior pelvic tilt and hip ROM also improved in the tuned condition compared to non-tuned.

Four out of five participants covered the most distance in the tuned condition (participants one, three, four and five) their speed was also highest in the tuned condition, compared to non-tuned. (See table 2 for temporal-spatial parameters).

Discussion

An increase in knee flexion during stance, outside the non-pathological range, seemed to be common in both non-tuned and tuned conditions (see figures 2 and 3). Jagadamma(19) also reported a tendency towards greater knee flexion throughout the stance phase with a tuned AFO-FC (compared to non-tuned) although changes were not statistically significant. Previous studies also report an increase in knee flexion at initial contact in a tuned AFO-FC(19,57), hypothesising that knee flexion at initial contact will increase in a tuned AFO-FC due to the enforced inclination of the shank. Knee flexion at initial contact in the current study, was decreased in participants one (compared to barefoot data) and four (compared to barefoot and non-tuned data) but increased in three out of the five participants (two, three and five). Importantly, knee flexion at initial contact also increased in the non-tuned condition (participants two, three, four and five) compared to barefoot data. It is important to note that the increase in knee flexion at initial contact in a tuned AFO-FC, reported by Jagadamma (19), was not statistically significant and the data were not compared to the participant's barefoot data, similarly Butler et al (57) did not provide data on the effect of knee flexion at initial contact in non-tuned AFO-FCs.

It is accepted that an extended knee (5°) at initial contact has the advantage of being the most stable weight bearing position(17), as such, it has been claimed that increased knee flexion at initial contact is a disadvantage(57). This study is the first to provide individual data sets for all three conditions (barefoot, non-tuned and tuned) and indicates that an increase in knee flexion at initial contact was also present in non-tuned AFOs. Thus, clinicians need to be mindful of the possible consequences of increased knee flexion at initial contact when prescribing tuned AFOs, including the effects on children with reduced power in the quadriceps who may have difficulty restraining a flexed knee and similarly those with weak hip extensors. One must be equally aware that a non-tuned AFO can also induce similar effects. The long-term effects of increased knee flexion at initial contact in an AFO are unknown and requires further investigation.

As previously explained, the position of the knee at TMST is crucial to stability in stance and the ability of the body to progress forward over the stance limb without inducing hyperextension of the knee. At TMST case study one demonstrated knee hyperextension (-1.04° (SD 3.29)) in the non-tuned condition, in the tuned condition the knee was flexed at 17.08° (SD 3.7), allowing forward progression over the stance limb. There was very little difference in knee flexion at TMST in a tuned and non-tuned AFO-FC for case study two, three and four. However, case study five demonstrated knee flexion of 4.14° (SD 6.18) at TMST in the non-tuned condition which improved to within non-pathological parameters in the tuned condition (16.86° (SD 1.59)).

Participants one and five showed the most improvement in all parameters tested, crucially, these two participants also demonstrated the most improvement in the knee at TMST which contributes to stability, a pre-requisite for normal gait(46). In addition, both had similar gait patterns (Winter's group II(12)), where the predominant feature was hyperextension of the knee at mid-stance, thus supporting previous research which highlighted the effectiveness of AFO-FC tuning in reducing hyperextension of the knee in children with CP(19).

Another explanation may be due to both of these participants having full passive range of motion in the hamstrings as noted in the physical assessment (see supplementary file for physical assessment table), hamstring tightness above 50° is considered abnormal(58). These participants also had less than 20° knee flexion during the first third of stance phase, which is an indicator for successful tuning(57).

Similarly, the three participants who showed the least improvement also had similar gait patterns (Winter's group IV(12)). This supports Jagadamma's(19) finding that the effects of tuning were different on the knee kinematics of participants with different gait patterns and Butler et al.'s (57) finding that a popliteal angle greater than 45° is a poor prognostic sign for successful tuning of the knee in stance phase. However, although these participants didn't show an improvement in knee kinematics with a tuned AFO-FC, improvements were seen in hip and pelvic kinematics. Butler et al.(57) would not have known this as their paper focused on kinematics of the knee joint and did not investigate the effect of AFO-FC tuning at the hip joint. Hip extension at terminal stance. is crucial in allowing knee extension and creating the "big V" (44,46) which offers a stretch to the musculature of the lower limb.

The results of this study indicate that improvements in kinematics can be made at the hip and pelvis in children with CP who have a hamstring contracture. This supports Owen's(59) view that the success of AFO-FC tuning may be limited by the inability to achieve full or nearly full extension at the knee and hip but that tuning can still produce positive results in such cases. Perry's(17) claim that when a subject's knee flexion matches hip flexion there is an improvement in pelvic and trunk kinematics, might offer an explanation for the improvements in pelvic kinematics demonstrated in this study, further research is required to determine the effects of AFO-FC tuning on trunk and upper limb kinematics.

This research is the first to provide individual case-series analysis of the effects of AFO-FC tuning on the kinematics of gait in children with CP, whilst the results of previous studies provide group mean data only. The results of this study indicate that tuning AFO-FCs can potentially improve hip, pelvic kinematics, knee extension in stance phase and knee flexion during swing phase in children with CP and that a non-tuned AFO-FC can potentially cause a deterioration in hip kinematics and posterior pelvic tilt. Importantly, the results show that a non-tuned AFO-FC has the potential to increase knee extension in participants whose predominant gait feature is hyperextension of the knee.

Although this study only provides data from a small number of participants, the results pave the way to design further structured studies with accepted statistical power.

Limitations of the study

The sample size for this study was small, a larger sample size is required to verify the results of this study.

All the participants had their initial gait assessed by the orthotist in clinic which determined the AFO prescription, without any kinetic or kinematic data available, as is common in clinical practice in the National Health Service (NHS). Thus, in one case (case study two), it is possible that a ground reaction force AFO (GRAFO) may have improved this participant's gait but unfortunately the extent of the knee flexion in stance was only picked up with the aid of the kinetic and kinematic data. Thus, supporting Owen's(43) that gait is too fast to pick up visually all the phases of the gait cycle.

Data were not presented for a footwear only condition and this could also be viewed as a limitation; however, it would have been impractical to collect a further trial of data on the same day by introducing another condition (footwear only). To do this would have resulted in an additional day of data collection and this is unlikely to have been accepted by the participants who already had to travel a significant distance to the University gait laboratory to take part in the study.

The data from this research was processed using the Vicon Plug-in-Gait model. This model contains numerous simplifications, e.g. the hip joint centres are based on manufacturer specific anthropometric regression equations, rather than functional models(60). This can cause both random and systematic errors in the hip centre location(60,61). However, both the model and the inherent errors are commonly used in clinical gait analysis and are representative of most conventional gait analysis models(60).

Finally, although the study aimed to compare the kinematics of non-tuned versus tuned AFO-FCs in children with CP, the non-tuned prescriptions had the correct angle of the ankle in the AFO (AAAFO)(59,62,63), which does not represent current clinical practice. Eddison et al.'s(64) research on common clinical practice in the U.K, with regards to AFO-FC tuning, indicated that the AAAFO chosen in AFO prescriptions doesn't necessarily represent the length of the gastrocnemius. Therefore, it is hypothesised that a non-tuned AFO with an AAAFO which doesn't accommodate the length of the gastrocnemius would cause gait to deteriorate further. A study on the effects of incorrect AAAFOs is required to learn more about the potential effects of this crucial aspect of biomechanical optimisation of AFOs.

Conclusion

A tuned AFO-FC can offer improvements in hip and pelvic kinematics in children with CP, the extent of improvements in knee kinematics appears to be dependent on the presenting gait pattern. A gait pattern similar to Winter's group II(12) demonstrated the most improvements in a tuned AFO-FC, and that the position of the knee at TMST seems to be an important aspect of the success of AFO-FC tuning on knee kinematics. Non-tuned AFOs can potentially increase hyperextension of the knee at mid-stance in participants whose main pathology is knee hyperextension. The results indicate that AFO-FC tuning is an important aspect of AFO treatment and prescription.

Brief summary

● The current literature lacks research on the effects of tuning ankle foot orthoses-footwear combinations on the kinematics of children with cerebral palsy.

● There is no available research on ankle foot orthoses-footwear combination tuning which provides individual data sets for participants. This study is the first to provide such data.

● Ankle foot orthoses-footwear combination tuning has the potential to improve hip function, pelvic function, knee extension in stance phase and knee flexion during swing phase.

● The effects of ankle foot orthoses-footwear combination tuning differ between different gait patterns. Non-tuned ankle foot orthoses can potentially increase hyperextension of the knee at mid-stance in participants whose main pathology is knee hyperextension similar to Winter's group II gait pattern.

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Figure legend

Figure 1: Footwear with temporary tuning adaptations (a) and permanently tuned footwear (b).Figure 2: Pelvis and hip kinematic data for individual participants; pelvis tilt ROM (a), pelvic peak posterior tilt (b), pelvic peak anterior tilt (c), hip ROM (d), hip peak extension (e), hip peak extension (f) and hip peak flexion in stance (g). BF = barefoot; CS = case series; L = left; R = right; NP = non-pathological; NT = non-tuned; ROM = range of motion; T = tuned.

Figure 3: Knee kinematic data for individual participants; knee ROM (a), knee peak extension (b), knee peak flexion (c), knee flexion at IC (d), knee flexion at TMST (e) and knee peak flexion in stance (f). BF = barefoot; CS = case series; IC = initial contact; L = left; R = right; NP = non-pathological; NT = non-tuned; ROM = range of motion; T = tuned; TMST = temporal mid-stance.

Participant ID		1	2	3	4	5
Popliteal angle (degrees)	Left	12	45	48	56	40
	Right	19	52	52	40	40
Sub-talar joint PROM (degrees) (inversion/eversion)	Left	30/10	26/11	38/10	18/19	35/15
	Right	26/9	25/12	35/10	28/8	35/18
Leg length discrepancy (mm) (actual unless stated)		-15	-10	-10	-15 (-4 apparent)	-15
Foot posture Index Score	Left	8	6	6	8	6
	Right	8	10	6	10	8
Spasticity: Hamstrings	Left	0	0	0	2+	0
	Right	0	1	1	0	1
Spasticity: Quadriceps	Left	0	0	0	0	1
	Right	1	1	0	0	1
Spasticity: Dorsiflexors	Left	0	1	0	0	1+
	Right	1	2	0	0	2
Spasticity: Plantar flexors	Left	0	1	1	2+	1
	Right	3	2	1+	0	2
Muscle Power: Hamstrings	Left	5	5	5	5	5
	Right	5	5	5	5	4
Muscle Power: Hip flexors	Left	5	4	5	5	5
	Right	5	4	5	5	5
Muscle Power: Hip extensors	Left	5	5	5	5	5
	Right	5	4	5	5	5
Muscle Power: Hip Abductors	Left	5	5	4	5	5
	Right	5	5	4	5	5
Muscle Power: Hip Inv/Evertors	Left	5	5	5	5	5
	Right	2	5	5	5	5
Muscle Power: Dorsiflexors	Left	5	5	5	5	5
	Right	2	5	5	5	5
Muscle Power: Plantar flexors	Left	5	5	5	5	5
	Right	2	5	5	5	5
Gastrocnemius PROM dorsiflexion (degrees)	Left	18	5	6	-8	10
	Right	5	90	90	10	90
Soleus PROM dorsiflexion (degrees)	Left	30	14	21	90	21
	Right	12	3	12	21	90

Table 4: Physical assessment for each participant. Spasticity rating using the modified Ashworth Scale(1), muscle power using Oxford scale(2), and the foot posture index(3). PROM = passive range of motion.

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	Barefoot Mean (Mean (SD))					Non-Tuned (Mean (SD))					Tuned (Mean (SD))					Non-Pathological (Mean)
Participant	**1**	**2**	**3**	**4**	**5**	**1**	**2**	**3**	**4**	**5**	**1**	**2**	**3**	**4**	**5**	
Pelvic Kinematics																
Peak anterior pelvic tilt	9.52 (4.02)	25.45 (2.62)	10.08 (2.04)	12.10 (2.99)	13 (4.11)	10.1 (3.35)	28.99 (1.62)	14.07 (1.90)	14.8 (2.42)	11.35 (1.57)	10.48 (4.02)	12.2 (2.22)	12.80 (2.84)	16.28 (1.9)	13.12 (2.4)	12.9 (5.3)
Peak posterior pelvic tilt	5.11 (1.02)	19.9 (0.61)	5.25 (2.01)	2.8 (1.14)	4.63 (1.43)	5.2 (0.91)	19.97 (0.44)	6.75 (3.32)	5.53 (0.7)	2.5 (0.52)	7.79 (0.92)	5.04 (0.63)	8.54 (2.25)	7.22 (0.93)	1.9 (0.7)	10.9 (5.1)
Pelvic tilt ROM	4.41 (3.0)	5.57 (2.01)	4.83 (0.88)	9.33 (1.84)	8.38 (2.68)	4.86 (2.43)	9.03 (1.2)	7.32 (1.97)	9.28 (1.73)	8.88 (1.04)	2.7 (3.09)	7.14 (1.6)	4.26 (1.43)	9.1 (0.94)	11.22 (1.73)	2
Hip Kinematics																
Peak Hip flexion	40.4 (1.4)	51.09 (0.64)	38.06 (0.99)	34.00 (0.62)	31.74 (1.01)	41.3 (3.42)	54.13 (0.9)	34.22 (1.44)	28.28 (1.73)	31.92 (2.31)	40.2 (1.72)	40.29 (1.69)	37.79 (1.86)	32.57 (0.75)	34.23 (0.58)	37.5 (6)
Peak Hip extension	-15 (1.9)	20.3 (2.43)	-11.76 (3.98)	-2.67 (3.74)	-10.6 (4.23)	-13.8 (3.83)	15.7 (6.4)	-12.84 (6.5)	-5.81 (4.15)	-6.21 (5.82)	-10.6 (1.94)	-3.3 (4.9)	-6.35 (5.71)	-4.15 (2.63)	-7.72 (2.86)	-5.3 (6.8)
Peak hip flexion (stance)	27.2 (3.2)	50.56 (0.63)	33.89 (3.98)	25.7 (2.4)	24.1 (2.85)	32.3 (2.4)	52.40 (3.51)	30.84 (4.11)	23.76 (3.8)	29.7 (5.81)	39.1 (2.52)	37.52 (1.7)	37.47 (5.71)	32.57 (2.6)	33.7 (1.73)	36.37 (6.2)
Hip ROM	55.41 (5.17)	30.8 (1.8)	49.83 (2.98)	36.57 (3.12)	42.3 (3.22)	55.09 (4.12	38.45 (5.48)	47.08 (5.05)	34.05 (2.4)	38.08 (3.5)	50.83 (5.61)	43.6 (3.15)	44.15 (3.85)	36.72 (1.87)	41.92 (2.27)	42.72
Knee Kinematics																
Knee flexion at IC	11.26 (1.1)	18.76 (1.38)	22.71 (2.24)	22.19 (2.34)	13.65 (4.04)	5.96 (5.54)	25.32 (3.77)	23.01 (3)	25.5 (4.11)	17.85 (5.9)	9.07 (7.37)	30.06 (3.17	26.8 (2.66)	17.64 (2.87)	26.2 (1.6)	6.66 (5.24)
Knee flexion at TMST	-3.4 (3.62)	20.84 (0.1)	16.83 (3.21)	8.64 (1.14)	-2.4 (1.93)	-1.04 (3.29)	21.91 (6.1)	18.6 (6.12)	16.54 (2.57)	4.14 (6.18)	17.08 (3.7)	22.19 (6.5)	19.99 (5.62)	14.02 (1.25)	16.86 (1.59)	10.76 (5.49)
Peak knee flexion (stance)	13.9 (3.1)	27.60 (1.92)	29.24 (3.41)	22.42 (3.55)	5.29 (6.04)	17.5 (3.0)	30.36 (6.55)	32.28 (7.37)	28.08 (4.96)	22.97 (7.42)	24.4 (5.3)	35.30 (6.59)	37.02 (7.15)	24.01 (3.66)	35.48 (3.8)	19.52 (6.89)
Peak knee extension	-3.8 (0.9)	15.87 (0.43)	7.30 (1.43)	8.09 (1.11)	-3.84 (1.61)	-6.1 (1.55)	18.32 (0.77)	6.02 (1.76)	14.82 (1.38)	1.6 (2.27)	0.5 (2.1)	18.17 (1.65)	10.66 (2.59)	8.16 (1.22)	1.91 (0.96)	3.7 (5.3)
Peak knee flexion	74 (9.9)	63.89 (4.80)	60.91 (4.15)	55.19 (7.86)	57.42 (7.06)	72.8 (10.34)	59.77 (9.42	52.87 (7.70)	43.15 (5.5)	57.77 (12.52)	67 (8.04)	55.74 (9.86)	59.69 (9.06)	35.78 (5.95)	58.57 (5.85)	60.41 (3.69)
Knee ROM	77.71 (8.92)	48 (4.29)	53.54 (2.69)	47.03 (6.68)	61.23 (5.44)	78.91 (8.71)	41.41 (8.59)	46.68 (5.92)	28.3 (4.1)	56.13 (10.24)	66.29 (5.9)	37.57 (8.2)	48.91 (6.43)	27.56 (4.73)	56.66 (4.82)	56.72

Supplementary File 1: Pelvis, hip and knee kinematic data for individual participants.

Case study 1	Barefoot (SD)	Non-Tuned (SD)	Tuned (SD)	Non-Pathological (SD)
Pelvic Kinematics				
Peak anterior pelvic tilt	9.52 (4.02)	10.1 (3.35)	10.48 (4.02)	12.9 (5.3)
Peak posterior pelvic tilt	5.11 (1.02)	5.2 (0.91)	7.79 (0.92)	10.9 (5.1)
Pelvic tilt ROM	4.41 (3.0)	4.86 (2.43)	2.7 (3.09)	2
Hip Kinematics				
Peak Hip flexion	40.4 (1.4)	41.3 (3.42)	40.2 (1.72)	37.5 (6)
Peak Hip extension	-15 (1.9)	-13.8 (3.83)	-10.6 (1.94)	-5.3 (6.8)
Peak hip flexion (stance)	27.2 (3.2)	32.3 (2.4)	39.1 (2.52)	36.37 (6.2)
Hip ROM	55.41 (5.17)	55.09 (4.12	50.83 (5.61)	42.72
Knee Kinematics				
Knee flexion at IC	11.26 (1.1)	5.96 (5.54)	9.07 (7.37)	6.66 (5.24)
Knee flexion at TMST	-3.4 (3.62)	-1.04 (3.29)	17.08 (3.7)	10.76 (5.49)
Peak knee flexion (stance)	13.9 (3.1)	17.5 (3.0)	24.4 (5.3)	19.52 (6.89)
Peak knee extension	-3.8 (0.9)	-6.1 (1.55)	0.5 (2.1)	3.7 (5.3)
Peak knee flexion	74 (9.9)	72.8 (10.34)	67 (8.04)	60.41 (3.69)
Knee ROM	77.71 (8.92)	78.91 (8.71)	66.29 (5.9)	56.72
Case study 2	**Barefoot (SD)**	**Non-Tuned (SD)**	**Tuned (SD)**	**Non-Pathological (SD)**
Pelvic Kinematics				
Peak anterior pelvic tilt	25.45(2.62)	28.99 (1.62)	12.2 (2.22)	12.9 (5.3)
Peak posterior pelvic tilt	19.9 (0.61)	19.97 (0.44)	5.04 (0.63)	10.9 (5.1)
Pelvic tilt ROM	5.57 (2.01)	9.03 (1.2)	7.14 (1.6)	2
Hip Kinematics				
Peak Hip flexion	51.09 (0.64)	54.13 (0.9)	40.29 (1.69)	37.5 (6)
Peak Hip extension	20.3 (2.43)	15.7 (6.4)	-3.3 (4.9)	-5.3 (6.8)
Peak hip flexion (stance)	50.56 (0.63)	52.40 (3.51)	37.52 (1.7)	36.37 (6.2)
Hip ROM	30.8 (1.8)	38.45 (5.48)	43.6 (3.15)	42.72
Knee Kinematics				
Knee flexion at IC	18.76 (1.38)	25.32 (3.77)	30.06 (3.17	6.66 (5.24)
Knee flexion at TMST	20.84 (0.1)	21.91 (6.1)	22.19 (6.5)	10.76 (5.49)
Peak knee flexion (stance)	27.60 (1.92)	30.36 (6.55)	35.30 (6.59)	19.52 (6.89)
Peak knee extension	15.87 (0.43)	18.32 (0.77)	18.17 (1.65)	3.7 (5.3)
Peak knee flexion	63.89 (4.80)	59.77 (9.42	55.74 (9.86)	60.41 (3.69)
Knee ROM	48 (4.29)	41.41 (8.59)	37.57 (8.2)	56.72
Case study 3: Left	**Barefoot (SD)**	**Non-Tuned (SD)**	**Tuned (SD)**	**Non-Pathological (SD)**
Pelvic Kinematics				
Peak anterior pelvic tilt	10.08 (2.04)	14.07 (1.90)	12.80 (2.84)	12.9 (5.3)

Peak posterior pelvic tilt	5.25 (2.01)	6.75 (3.32)	8.54 (2.25)	10.9 (5.1)
Pelvic tilt ROM	4.83 (0.88)	7.32 (1.97)	4.26 (1.43)	2
Hip Kinematics				
Peak Hip flexion	38.06 (0.99)	34.22 (1.44)	37.79 (1.86)	37.5 (6)
Peak Hip extension	-11.76 (3.98)	-12.84 (6.5)	-6.35 (5.71)	-5.3 (6.8)
Peak hip flexion (stance)	33.89 (3.98)	30.84 (4.11)	37.47 (5.71)	36.37 (6.2)
Hip ROM	49.83 (2.98)	47.08 (5.05)	44.15 (3.85)	42.72
Knee Kinematics				
Knee flexion at IC	22.71 (2.24)	23.01 (3)	26.8 (2.66)	6.66 (5.24)
Knee flexion at TMST	16.83 (3.21)	18.6 (6.12)	19.99 (5.62)	10.76 (5.49)
Peak knee flexion (stance)	29.24 (3.41)	32.28 (7.37)	37.02 (7.15)	19.52 (6.89)
Peak knee extension	7.30 (1.43)	6.02 (1.76)	10.66 (2.59)	3.7 (5.3)
Peak knee flexion	60.91 (4.15)	52.87 (7.70)	59.69 (9.06)	60.41 (3.69)
Knee ROM	53.54 (2.69)	46.68 (5.92)	48.91 (6.43)	56.72
Case study 3: Right	**Barefoot (SD)**	**Non-Tuned (SD)**	**Tuned (SD)**	**Non-Pathological (SD)**
Pelvic Kinematics				
Peak anterior pelvic tilt	12.5 (3.8)	10.22 (3.72)	12.45 (2.31)	12.9 (5.3)
Peak posterior pelvic tilt	8.16 (2.36)	5.31 (1.8)	8.16 (1.23)	10.9 (5.1)
Pelvic tilt ROM	4.34 (1.44)	4.91 (1.97)	4.29 (1.08)	2
Hip Kinematics				
Peak Hip flexion	35.81 (2.18)	30.86 (1.7)	38.58 (0.8)	37.5 (6)
Peak Hip extension	-10.68 (3.87)	-12.46 (5.67)	-5.16 (3.23)	-5.3 (6.8)
Peak hip flexion (stance)	30.62 (3.87)	30.7 (5.65)	38.6 (3.23)	36.37 (6.2)
Hip ROM	46.44 (1.7)	43.27 (3.95)	43.7 (2.43)	42.72
Knee Kinematics				
Knee flexion at IC	20.49 (2.16)	23.85 (1.91)	30.06 (3.17)	6.66 (5.24)
Knee flexion at TMST	14.5 (2.4)	20.91 (3.4)	22.2 (6.5)	10.76 (5.49)
Peak knee flexion (stance)	27.39 (4.89)	34.06 (5.82)	35.3 (6.58)	19.52 (6.89)
Peak knee extension	7.71 (1.83)	11.17 (1.64)	18.17 (1.66)	3.7 (5.3)
Peak knee flexion	64.5 (6.01)	53.02 (5.8)	55.75 (9.9)	60.41 (3.69)
Knee ROM	56.8 (4.25)	41.85 (4.16)	37.6 (8.21)	56.72
Case study 4: Left Leg	**Barefoot (SD)**	**Non-Tuned (SD)**	**Tuned (SD)**	**Non-Pathological (SD)**
Pelvic Kinematics				
Peak anterior pelvic tilt	12.10 (2.99)	14.8 (2.42)	16.28 (1.9)	12.9 (5.3)
Peak posterior pelvic tilt	2.8 (1.14)	5.53 (0.7)	7.22 (0.93)	10.9 (5.1)
Pelvic tilt ROM	9.33 (1.84)	9.28 (1.73)	9.1 (0.94)	2
Hip Kinematics				
Peak Hip flexion	34.00 (0.62)	28.28 (1.73)	32.57 (0.75)	37.5 (6)

Peak Hip extension	-2.67 (3.74)	-5.81 (4.15)	-4.15 (2.63)	-5.3 (6.8)
Peak hip flexion (stance)	25.7 (2.4)	23.76 (3.8)	32.57 (2.6)	36.37 (6.2)
Hip ROM	36.57 (3.12)	34.05 (2.4)	36.72 (1.87)	42.72
Knee Kinematics				
Knee flexion at IC	22.19 (2.34)	25.5 (4.11)	17.64 (2.87)	6.66 (5.24)
Knee flexion at TMST	8.64 (1.14)	16.54 (2.57)	14.02 (1.25)	10.76 (5.49)
Peak knee flexion (stance)	22.42 (3.55)	28.08 (4.96)	24.01 (3.66)	19.52 (6.89)
Peak knee extension	8.09 (1.11)	14.82 (1.38)	8.16 (1.22)	3.7 (5.3)
Peak knee flexion	55.19 (7.86)	43.15 (5.5)	35.78 (5.95)	60.41 (3.69)
Knee ROM	47.03 (6.68)	28.3 (4.1)	27.56 (4.73)	56.72
Case study 5: Right	**Barefoot (SD)**	**Non-Tuned (SD)**	**Tuned (SD)**	**Non-Pathological (SD)**
Pelvic Kinematics				
Peak anterior pelvic tilt	13 (4.11)	11.35 (1.57)	13.12 (2.4)	12.9 (5.3)
Peak posterior pelvic tilt	4.63 (1.43)	2.5 (0.52)	1.9 (0.7)	10.9 (5.1)
Pelvic tilt ROM	8.38 (2.68)	8.88 (1.04)	11.22 (1.73)	2
Hip Kinematics				
Peak Hip flexion	31.74 (1.01)	31.92 (2.31)	34.23 (0.58)	37.5 (6)
Peak Hip extension	-10.6 (4.23)	-6.21 (5.82)	-7.72 (2.86)	-5.3 (6.8)
Peak hip flexion (stance)	24.1 (2.85)	29.7 (5.81)	33.7 (1.73)	36.37 (6.2)
Hip ROM	42.3 (3.22)	38.08 (3.5)	41.92 (2.27)	42.72
Knee Kinematics				
Knee flexion at IC	13.65 (4.04)	17.85 (5.9)	26.2 (1.6)	6.66 (5.24)
Knee flexion at TMST	-2.4 (1.93)	4.14 (6.18)	16.86 (1.59)	10.76 (5.49)
Peak knee flexion (stance)	5.29 (6.04)	22.97 (7.42)	35.48 (3.8)	19.52 (6.89)
Peak knee extension	-3.84 (1.61)	1.6 (2.27)	1.91 (0.96)	3.7 (5.3)
Peak knee flexion	57.42 (7.06)	57.77 (12.52)	58.57 (5.85)	60.41 (3.69)
Knee ROM	61.23 (5.44)	56.13 (10.24)	56.66 (4.82)	56.72

Table 3: Hip and knee kinematics during gait SD = Standard deviation. I.C = Initial contact: All values in degrees. TMST = Temporal mid-stance

Acknowledgements:

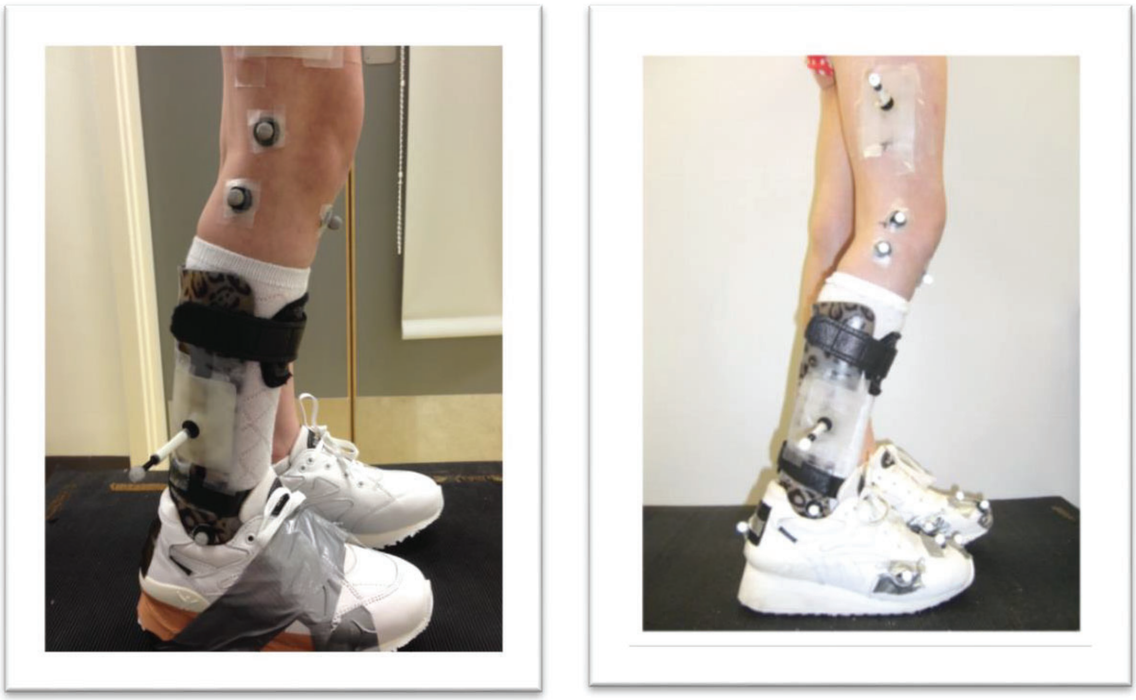
The authors would like to thank Salts Healthcare for providing the AFOs and over splint footwear for this study and to the Orthotic Education Training Trust for supporting the primary author's PhD research.

Fig 1 a Picture file

Fig 1 b Picture file

Click here to access/download;Figure;Fig_1b_kin_paper_foot.png

Figure 1 as it should appear in the manuscript



(a) (b)

Figure 1: Shoe with temporary tuning adaptations (a) and permanently tuned footwear (b).

Figure 2

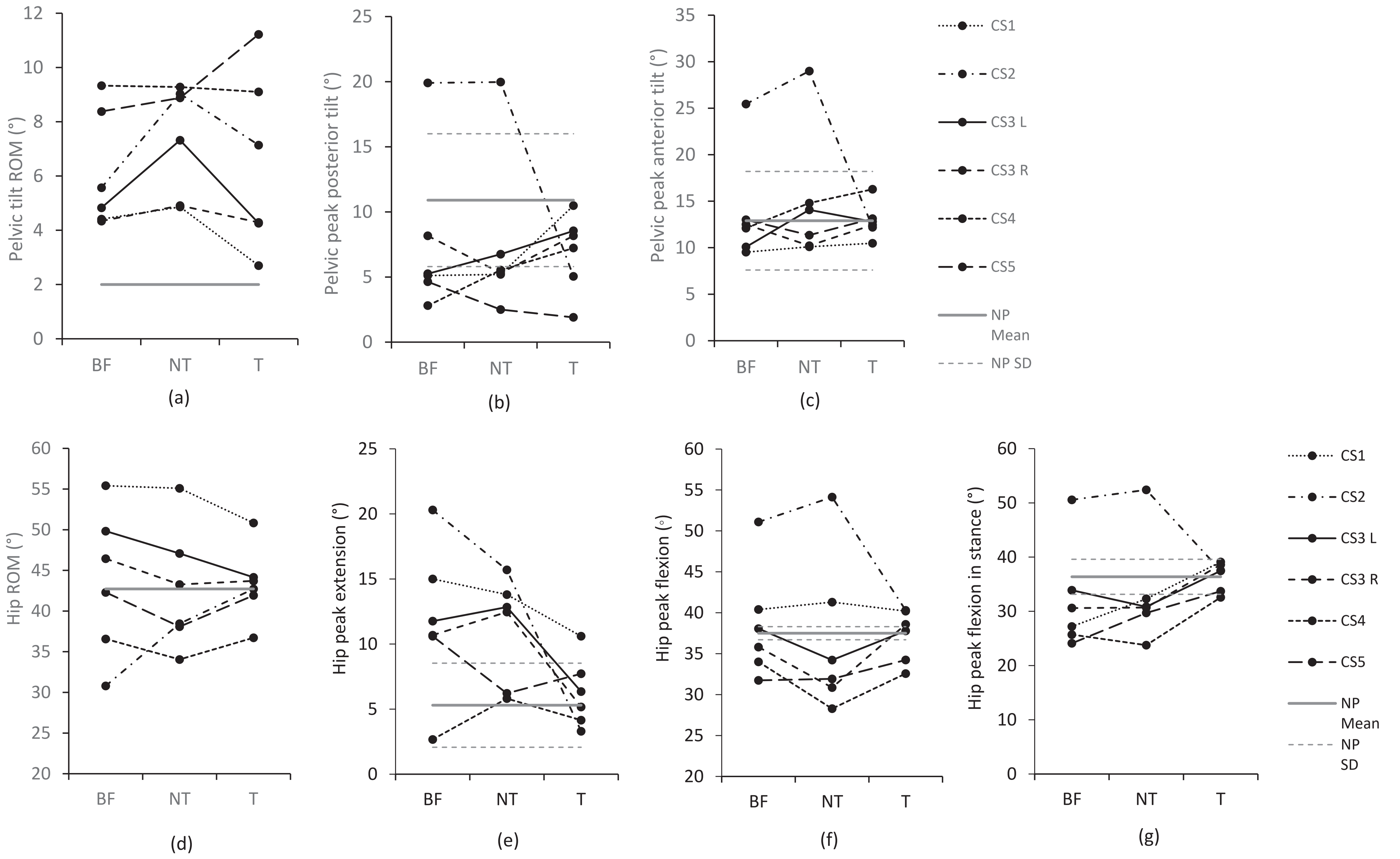


Figure 2: Pelvis and hip kinematic data for individual participants; pelvis tilt ROM (a), pelvic peak posterior tilt (b), pelvic peak anterior tilt (c), hip ROM (d), hip peak extension (e), hip peak extension (f) and hip peak flexion in stance (g). BF = barefoot; CS = case series; L = left; R = right; NP = non-pathological; NT = non-tuned; ROM = range of motion; T = tuned.

Figure 3

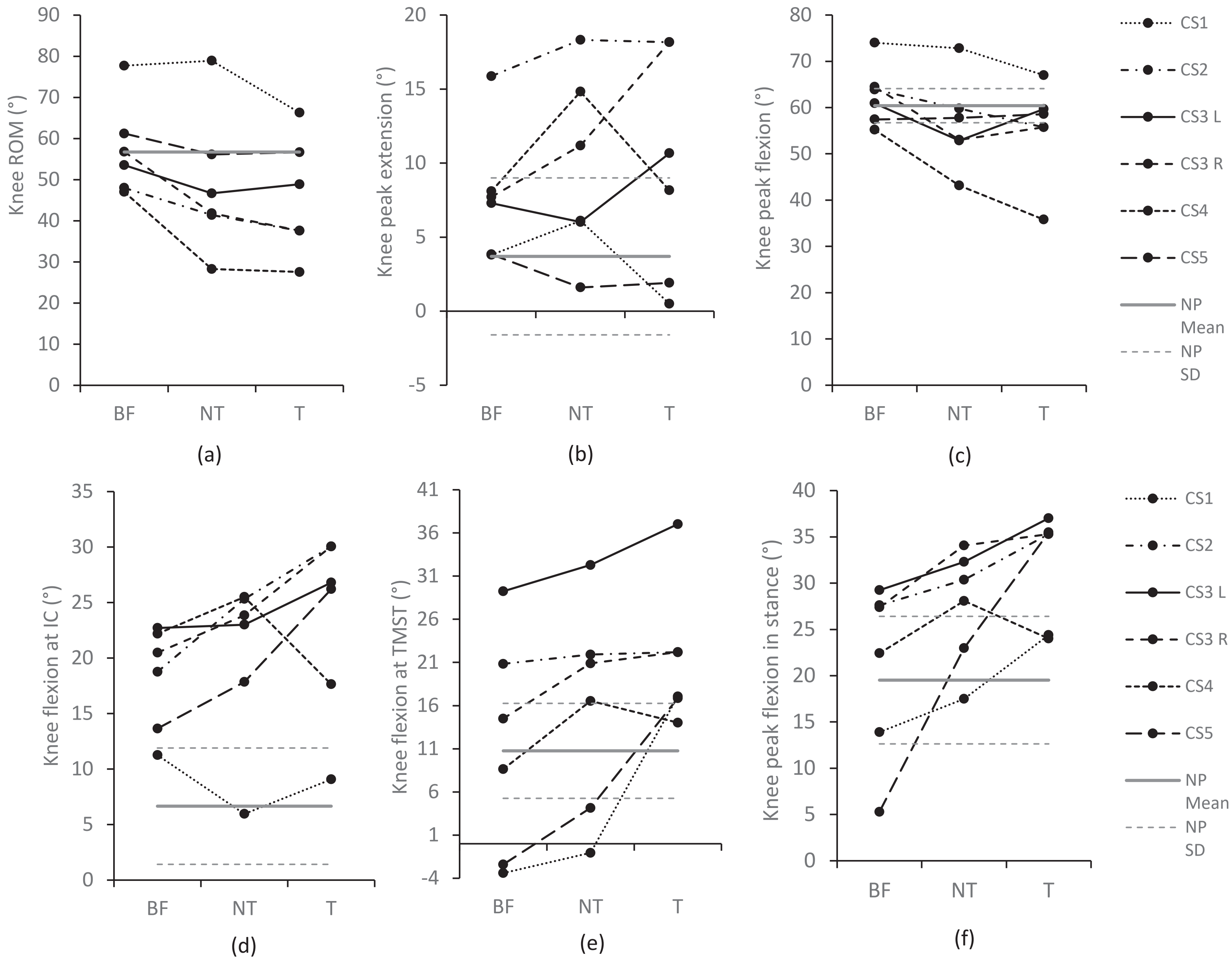


Figure 3: Knee kinematic data for individual participants; knee ROM (a), knee peak extension (b), knee peak flexion (c), knee flexion at IC (d), knee flexion at TMST (e) and knee peak flexion in stance (f). BF = barefoot; CS = case series; IC = initial contact; L = left; R = right; NP = non-pathological; NT = non-tuned; ROM = range of motion; T = tuned; TMST = temporal mid-stance.

Table 1

Participant ID	1	2	3	4	5
CP Classification	Spastic hemiplegic right side affected	Spastic diplegic with right side predominately affected AFO right only	Spastic diplegic	Spastic diplegic with left side predominately affected	Spastic diplegic with right side predominately affected
Sex	F	M	F	M	M
Body Mass (kg)	23.6	55.1	27.7	31	25.8
Age (Years)	8	11	7	10	9
Height (cm)	122	145	131	140	131
Passive length of gastrocnemius with knee extended	5° dorsiflexed	90°	90°	8° plantar flexed	90°
Barefoot gait classification (Winters (12)	Group II	Group IV	Group IV	Group IV	Group II
AAAFO	90°	90°	90°	8° Plantar Flexion SAB 90°	90°
AFO	Right solid AFO	Bilateral Solid AFO	Bilateral Solid AFO	Left Solid AFO	Right solid AFO
Material/thickness	Homopolymer Polypropylene	Homopolymer Polypropylene	Homopolymer polypropylene	Homopolymer Polypropylene	Homopolymer Polypropylene
Material Thickness	4.5mm	5mm	4.5mm	4.5mm	4.5mm
Foot Plate	Full length with lateral flange distal to 5th MTPJ to control fore foot abduction. Flexible at the MTPJs to facilitate 3rd rocker. Flexible sole rounded profile.	Full length, M-L flanges distal to MTPJs o block 3rd rocker and limit knee flexion during stance. Sole unit stiffened with a rounded forefoot rocker	Full length, carbon fibre stiffener. M-L flanges distal to MTPJs to block 3rd rocker and limit knee flexion. Sole unit stiff with a point loading rocker	Full length, M-L flanges distal to MTPJs to block 3rd rocker and limit knee flexion. Sole unit stiffened with a rounded forefoot rocker.	Full length, M-L flanges proximal to MTPJs flexible to facilitate 3rd rocker. Flexible sole, rounded profile.
Optimum SVA	12°	12°	13°	13°	11°

Table 1: Participant anthropometric and ankle foot orthosis (AFO) design information. (AAAFO = angle of the ankle in the AFO, SVA = shank to vertical angle, SAB = shank angle to bench))

Table 2

	Barefoot Mean (Mean (SD))					**Non-Tuned (Mean (SD))**					**Tuned (Mean (SD))**					**Non-Pathological (Mean)**
Participant	**1**	**2**	**3**	**4**	**5**	**1**	**2**	**3**	**4**	**5**	**1**	**2**	**3**	**4**	**5**	
Left Step Length (m)	0.49 (0.03)	0.48 (0.03)	0.48 (0.03)	0.36 (0.03)	0.50 (0.03)	0.52 (0.05)	0.58 (0.04)	0.46 (0.04)	0.44 (0.05)	0.55 (0.04)	0.58 (0.08)	0.61 (0.03)	0.46 (0.03)	0.43 (0.03)	0.51 (0.03)	0.57
Right Step Length (m)	0.45 (0.04)	0.55 (0.02)	0.45 (0.03)	0.43 (0.03)	0.47 (0.02)	0.54 (0.04)	0.48 (0.04)	0.45 (.03)	0.53 (0.05)	0.49 (0.49)	0.56 (0.04)	0.48 (0.07)	0.46 (0.03)	0.56 (0.03)	0.48 (0.02)	0.57
Cadence (Steps/Minute)	130.21 (14.7)	115 (3.5)	139.37 (9.36)	87.9 (6.7)	112.31 (4.6)	128.19 (8.73)	108.65 (6.16)	117.3 (10.95)	92.95 (9.81)	109.84 (9.5)	110.68 (9.21)	113 (9.41)	112.83 (11.29)	106.62 (7.1)	103.54 (3.4)	123.18
Walking speed (Metres per minute)	71.25(16.5)	41.48 (10.2)	46.27 (7.14)	36.4 (7.75)	56.66 (4.63)	65.5 (21.75)	51.19 (0.97)	44.29 (11.46)	45.6 (15.5)	56.13 (8.5)	69.5 (7.5)	44.75 (5.43)	52.39 (7.52)	49.91 (8.5)	57.17 (17.25)	69.6
Distance covered (m)	285 (66)	165.93 (40.81)	185.1 (28.56)	145.6 (31)	226.6 (18.5)	262 (87)	204.8 (3.82)	177.2 (45.86)	182.7 (62)	224.5 (2)	278 (30)	190.4 (37.2)	210.2 (27.2)	199.7 (34)	227.3 (65)	

Table 2 Temporal-spatial parameters. Distance and speed are calculated as the mean average of the total distance/speed in 3 x 4-minute trials.