# Exploring the relationships between terrain, structural foot morphology, and adaptive foot morphology

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# Abstract

The arch of the foot is considered a principal element of the structure and function of the foot, and its claimed causative relationship with injuries has been commonly researched. The impact of terrain (Natural and Developed) on the development of the arch has not yet been clearly researched and could be a critical part in the structure-function-injury discussion. Collecting postcodes and Foot Flexibilities (FF) from a range of participants and data gathered using smart insoles allowed for relationships between terrain, foot structure, dynamic response, and the biophysics of the foot to be examined.

Young participants growing up on a Natural terrain were found to have a more flexible arch; however, the same was not observed in an adult population. High FF feet and low FF feet did not yield significantly different values for walking characteristics, nor did they show a difference in adaptability to walking on varying terrains. Moreover, no correlations could be found between FF and walking characteristics. It was found, however, that the dynamic response of the foot differs between varying terrains. Few correlations were observed between terrains per walking characteristic, and the characteristics themselves did not appear interrelated either. Lastly, it was shown that a more deforming arch stores more energy than a rigid arch.

Terrain has been shown to influence the foot structure of a developing foot, but a standardised protocol to classify terrains is required to observe this trend consistently. Pronation was often found to be the outlier in general trends, facilitating development of the theory that pronation is inherent to the foot, undecided by environmental factors or correlated to certain intrinsic classifications. The vertical displacement of the arch was found to be the main cause of higher energy storage in flexible arches, although calculations leading to this observation were based on simplifications of the mechanisms.

## Acknowledgements

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# 1. Introduction

The foot arch is considered the predominant structure in absorbing shock and determining foot function[1]; similarly, arch flexibility is found to be a descriptor of foot structure and function[2]. A general consensus is found that planus or cavus foot types are more prone to injuries than rectus foot types, but a consensus is lacking on which foot type classification method is most accurate and widely applicable. The relationships of intrinsic and environmental factors with foot characteristics are also unclear following available research. It is currently unknown whether the terrain type an individual grows up on affects their foot structure. More insight into the relationships between foot structure, function, biomechanics, and pathologies and their significance could assist medical services to continue to research these relationships**,** as foot structure has been said to relate to injury patterns in the lower extremities[3,4,5,6].

This research aims to investigate whether the terrain an individual grows up on has an impact on the foot structure around the age of foot development. Then, it is studied whether this relationship persists into adulthood, as well as whether certain foot structures interact differently with terrain and changes therein. Additionally, it is examined whether terrain walked on influences walking characteristics concurrently. Lastly, the biophysics of the foot is considered, where possible relationships between foot structure and the arch's function as a spring are studied, with the aim of elucidating the relationship between foot structure and foot function.

## 1.1. Literature review

Feet take on different morphologies throughout the gait cycle, when standing or when sitting down. Many objective measures are available to classify feet into certain groups of structure. These methods are applied to enable comparison and conclusions to be drawn, for example about function, mobility, and health.

Much research is dedicated to exploring the relationships between foot characteristics and pathologies. Before any relationship concerning foot shape, structure, function, injury and so forth can be explored, a reliable method of classifying characteristics must be followed within the research. Ideally, a validated method is applied consistently across all research into such relationships. The use of one universally applied method would eliminate a foundational variable while studying an intricate subject and consequently allow studies to be compared and pooled more easily to facilitate more robust knowledge to be gained.

### 1.1.1. Classification of feet

In order to compare feet in both a research and clinical setting, a classification system is required[7]. The classification of foot types and characteristics simplifies the anatomical complexities of feet, enabling this comparison[8] and are typically based on the static morphology of a foot. It is generally assumed that a foot with a particular structure will display certain functional characteristics related to both the foot and the lower extremity as a whole[6,9]. This assumption has been questioned[10] and refuted[11]. Foot type, structure, function and flexibility can be used to form separate classifications or can be used selectively in conjunction to form a more comprehensive classification.

The different foot types are planus, rectus and cavus and are based on the foot structure which categorises the arch as low, normal or high respectively[12,13].
Researchers have varying convictions of the best way to simplify and classify feet. For example, R.A. Zifchock et al. (2017) suggest that both arch flexibility and arch height are required to describe foot structure[7]. Alternatively, R. Mootanah et al. (2013) assessed foot structure by malleolar valgus index, arch height index, and arch height flexibility and have concluded that foot structure and function are related in asymptomatic healthy individuals[11].

Similarly, H.J. Hillstrom et al. (2013) have found the arch height index (measure of the dorsal arch height normalized to foot length (section 1.1.3) for sitting and standing to be significantly different between foot types, as well as the malleolar valgus index (a measure of standing hind foot alignment)[14]. Alternatively**,** S.P. Schultz et al. (2017) proposed that in order to classify a certain foot type, the foot structure, as well as function and flexibility should be considered[12,8]. Foot function relates to the level of pronation, which can be classified as over-pronation, normal or over-supination (under-pronation) (Figure 1) and reflects which part of the foot bears weight[12]. Foot flexibility is categorized as reduced, normal and excessive[12].

P.R. Cavanagh et al. (1997) have researched the relationship between the structure and function of feet, concluding that a small number of structural measurements can explain approximately 35% of plantar pressure distribution under the heel and the first metatarsal head[9]. Although this demonstrates some causation between the static structure of a foot and its dynamic function, the majority of foot function is influenced by other dynamic variables such as gait and walking velocity. A review of other anthropometric studies concluded that a variety of functional characteristics such as flexibility, foot type and alignment are important contributors to changes in gait biomechanics in the lower extremities[15].

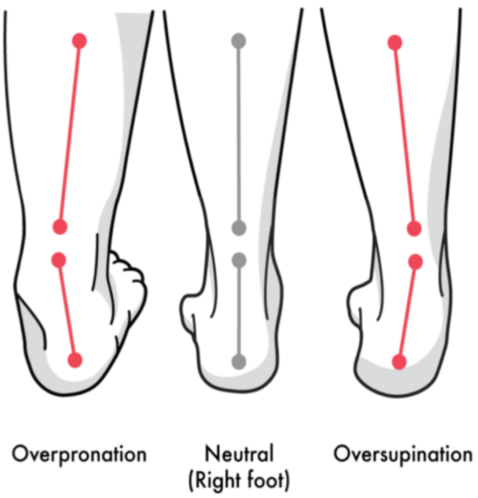


*Figure 1: Adopted image illustrating levels of pronation of the right foot[16].*

It is clear that a gold standard for categorizing foot type is lacking; a need for a reliable and objective measure to observe foot structure has been emphasized through a survey among physical therapists[8]. Despite the variation in manner of categorisation, the resultant foot types are used to explain variability of foot structure[13].

It is thought that the level of pronation influences the distribution of ground reaction forces (GRF) throughout the foot; over-pronated feet would cause the GRF to move medially throughout the stance phase and over-supinated feet, laterally[14]. This has been confirmed by comparing the centre of pressure of the foot between high arched and low arched runners[17]. While the relative placement of the GRF may differ between foot types, the magnitude of the force is found to be statistically uninfluenced by foot types[18]. This can be explained by the fact that as the heel strikes the ground, the forefoot, and therefore the arch, are not yet in contact with the ground and therefore not involved in the absorption of the GRF. Similarly, the effect of arch flexibility on the average vertical GRF was found insignificant[18]. Contrastingly, another study found that rigid-arched runners had a greater second vertical GRF peak[2], implying that arch mobility would, in fact, influence the GRF experienced.

Conflicting results are reported regarding the structure of a foot and its effect on loading and forces on the lower extremities. Williams et al. (2014) conducted on a healthy adult population has found that a resting foot has a slightly pronated structure in normal position[19]. This is supported by H.J. Hillstrom et al. (2013) who conclude that planus feet are generally in an over pronated position. Consequently, the force exerted on a foot by the ground (ground reaction force) moves through the lower extremities medially during walking. Conversely, cavus feet typically over supinate causing the ground reaction force to move laterally through the lower extremities[14].

P.R. Cavanagh et al. (1997) confirm the notion that cavus feet experience a high plantar pressure as their analysis predicts that a greater angle between the first metatarsal and the supporting surface would lead to increased pressures under the rearfoot and the forefoot[9]. The level of inclination of the first metatarsal relates linearly to the medial longitudinal arch height, which differs between foot types. However, as previously mentioned, the mathematical analysis only accounts for 35% of the plantar pressure, which could prompt the discussion of whether the correlation between foot type and plantar pressure is due to a causal effect. Conflictingly, D.S.B Williams et al. (2014) report that while the static arch structure does influence lower extremity movement, its effect on forces through the lower extremities is, however, less conclusive[2].

### 1.1.2. Foot type as a propensity for injury

One main reason for researching widely applicable and reliable methods of classifying feet is that foot structure is said to influence the propensity to sustain lower extremity injuries[5,3,4,6,17]. Abnormal walking or running could cause anomalous forces on the body, resulting in injuries[20]. If feet classification can be standardized, investigations into the correlation of foot structure with foot function – and dysfunction can be widely performed and compared more extensively. If direct relationships were to be discovered, more focussed research into preventative measures for injuries for people with certain foot types would be made possible. Ultimately, this would increase overall wellbeing and prosperity, saving both healthcare and society time and money.

Neutrally aligned feet were found to have a lower percentage of intrinsic muscle atrophy in a diabetic population[21]. Additionally, risk factors for lower extremity overuse injuries have been identified to include pes cavus, dynamic pes planus, restricted ankle dorsiflexion and increased hindfoot inversion. The research suggested there might be potential for managing and possibly correcting these predispositions[22]. When investigating a potential relationship between excessively pronated feet (n = 23), neutral feet (n = 24) or excessively supinated feet (n = 8) and ankle sprains and knee pain, results showed that athletes with pronated and supinated feet presented with significantly more knee pain than the athletes with a neutral foot type. A lack of significant relationship between foot type (pronated, neutral, supinated) and ankle sprains was also reported[6]. Beckett et al. (1992) related the amount of arch deformation between weight-bearing and non-weight-bearing to a knee injury[23]. However, this study was performed using individuals who had previously sustained the injury, so arguably direct causation could not be established.

More specifically focussed research published more nuanced results stating that runners with high-arched feet (n = 20) sustain more foot and ankle injuries, bony injuries and lateral injuries, and that runners with low-arched feet (n = 20) sustain more knee injuries, soft tissue injuries and medial injuries[17]. Where previously, excessively divergent feet were compared to neutral feet to yield a significant difference, but not between themselves[6], the two structure types on both ends of the spectrum are compared and each show different injury patterns. A logical conclusion is drawn that pronated feet experience increased stress on the medial structures of the lower extremity[17].

Research into the correlation between pes planus and lower extremity injuries has revealed that pes planus on the left foot has statistically significant relationships with injuries to the left midfoot, right midfoot and the left knee, whereas pes planus on the right foot showed a statistically significant relationship with right knee injuries. Additionally, the degree of pes planus as well as foot size was found to yield a statistically significant relationship with the total number of injuries. More specifically, it was shown that women's smaller feet, although exhibiting pes planus to a lesser degree, possess a smaller midfoot ratio (midfoot contact area as a percentage of total contact area[24]), but sustain a larger number of injuries[3]. The relationship of the size of the midfoot to injuries sustained is to be expected as the midfoot structure absorbs shock and forces associated with walking; a smaller surface area would therefore have a decrease in shock absorption ability as a consequence. The result that a flat left foot impacts the right midfoot seems unlikely. It could be considered that the right foot potentially compensates for the left foot's over-pronation, however the lack of mirrored relationship suggests this may be a statistical anomaly.
These results are said to arise from following a previously applied method[24], where conversely no evidence was found of pes planus causing a susceptibility to subsequent lower extremity injuries. Different research reported results stating a linear relationship between higher incidence of injury and increasingly higher arched feet[4]. Similarly, foot type was again not found to be a major risk factor for injury, but athletes with a supinated foot type were found to be four times more likely to sustain an overuse injury[5].

Considerable research has been performed to investigate the extent of the relationship between a foot's morphological characteristics and a predisposition to sustaining lower extremity injuries. Although not unanimous, the general conviction is foot type influences propensity to injuries sustained in the lower extremities in particular.
Pronation and supination are reported to play a determining part in the distribution and type of injuries or pain sustained[3,17]. However, consensus of research cannot be pooled without taking different methodologies of foot classification applied in the process of drawing these conclusions into consideration.

Despite conducted research, the specifics of how and why foot morphologic characteristics are associated with pathologies and why some individuals with non-rectus foot types are asymptomatic is unclear[14]. This raises the question if establishment of a direct relationship is possible. Prior to reaching that conclusion, classification language must be standardised, and a universal understanding must be gained about the way foot type interacts with structure and function[14].

### 1.1.3. Arch Height Index

*The arch height index*

Calculation of the arch height index (AHI) is a commonly used anthropometric approach to characterise the foot through two simple measurements[10]. The arch height index quantifies the height of the arch by normalising the dorsum height to the length of the truncated foot[25,26], and can be used to differentiate between individuals with low and high arches[26]. The AHI can be compared between people with differently sized feet and compared to an individual's own previously calculated AHI[8]. This has the added benefit that a child's foot structure can be tracked through development, thereby facilitating visualisation of any foot structure changes. Additionally, the normalisation of the arch height to the foot length is said to increase reliability and validity compared to absolute values[10].

*Calculation and interpretation of the arch height index*

The AHI is calculated by dividing the dorsum height (DH) by the truncated foot length (TFL)[27] (Equation 1). The dorsum height is measured from the flat surface on which the foot is placed to the top of the foot at half of the foot length (Figure 2). The truncated foot length is measured from the most posterior point of the calcaneus to the first metatarsal head along the medial border[27]. These measurements can be taken in both standing and sitting positions, with equal or pre-determined weight distribution between both feet.

$$AHI = \frac{Dorsum\ height}{Truncated\ foot\ length}$$

*Equation 1: Arch Height Index*

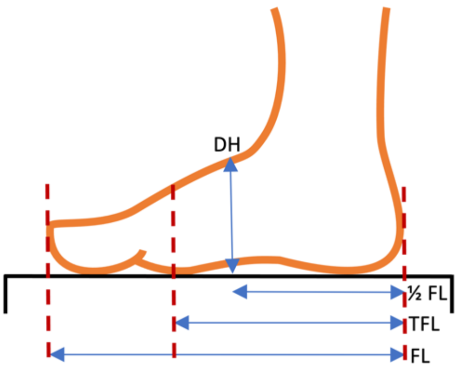


*Figure 2: Side view diagram of a foot illustrating the dorsum height (DH), foot length (FL), truncated foot length (TFL) and a half foot length (1/2 FL).*

The dorsum height is higher when it bears less weight (for example when sitting down) and therefore decreases upon standing up. Equally, the foot is shorter when it bears less weight and gets longer with an increase in weight-bearing. Consequently, a "rounder" foot (high arch, shorter TFL) when sitting results in a higher AHI compared to when standing (low arch, long TFL).

There are no absolute values denoting a good or bad classification for an AHI. However, various studies have calculated and published AHI values for a range of healthy populations as is shown in Table 1, where the mean AHI ± standard deviation (SD) are noted. One study also published the standard error measurement (SEM). An AHI value closer to zero indicates a flatter foot and a value closer to 0.5 indicates a higher arch.

The range encountered in publication (Table 1) allows for the observation of overlap in the values for sitting and standing measurements of AHI. The range published for AHI-sitting values is between 0.316 and 0.40. The range published for AHI-standing data is between 0.292 and 0.38. Although within the individual studies the mean AHI-sitting was found to be greater than the mean AHI-standing, an overlap between sitting and standing values is found across studies. A clearer separation between the compiled data of the two groups would have supported the classification method more.
The difference observed within the compiled data could be due to the method of collecting data. Utilizing callipers rather than the Arch Height Index Measuring System (AHIMS) (Table 1) results in the lowest AHI-sitting and AHI-standing values[27]. Without the values obtained with callipers, the overall ranges would be 0.35 – 0.40 for AHI-sitting and 0.32 – 0.38 for AHI-standing. No obvious differences in data can be observed as a result of gender or age. When participants were separated by their foot type (planus, recuts, cavus), mean AHI values for each foot type were presented[14].

*Table 1: Comparison of AHI values found in literature, showing population and method of measuring. The mean AHI ± standard deviation (SD) is noted. One study also published the standard error measurement (SEM). Weight-bearing (WB) percentages are included in the heading.*

| Publication | Population | Method | AHI-sitting (10% WB) | AHI-standing (50% WB) | AHI-standing (90% WB) |
|---|---|---|---|---|---|
| M.B. Pohl et al. (2010)[26] | 14 women, 6 men. Aged 29.9 ± 5.8 years. | AHIMS | 0.375 ± 0.020 | 0.345 ± 0.025 | 0.342 ± 0.024 |
| D.S. Williams et al. (2000)[27] | 28 women, 23 men. Aged 27.1 ± 6.1, range 19 – 43 years | Callipers | 0.316 ± 0.027 SEM 0.003 | | 0.292 ± 0.027 SEM 0.003 |
| R.J. Butler et al. (2008)[25] | 50 female and 50 male recreational runners. Aged between 18 – 45 years | AHIMS | 0.363 ± 0.030 | 0.340 ± 0.030 | |
| W.H. Weimar et al. (2013)[28] | 79 women. Aged 21.53 ± 1.5 years | AHIMS | 0.355 ± 0.031 | 0.338 ± 0.031 | |
| | | | 0.369 ± 0.034 | 0.343 ± 0.033 | |
| L.C. Drefus et al. (2017)[8] | 9 girls and 21 boys, aged 6 – 12 years old | AHIMS | 0.36 ± 0.02 | 0.32 ± 0.02 | |
| S.P. Shultz et al. (2012)[15] | 10 children, aged 8 – 12 years old | AHIMS | 0.35 ± 0.04 | 0.33 ± 0.04 | |
| H.J. Hillstrom | Planus: 12 women, 10 men. Aged 35.6 ± 11.0 years | AHIMS | 0.35 ± 0.03 | 0.33 ± 0.03 | |

| | | | | | |
|---|---|---|---|---|---|
| et al. (2013)[14] | Rectus: 19 women, 8 men. Aged 33.1 ± 9.8 years | | 0.38 ± 0.03 | 0.36 ± 0.03 | |
| | Cavus: 6 women, 6 men. Aged 42.8 ± 16.2 years | | 0.40 ± 0.03 | 0.38 ± 0.03 | |

In the first data row of Table 1, a reduction of 0.03 between 10% weight-bearing (WB) and 50% WB and a reduction of 0.003 between 50% WB and 90% WB is observed in the AHI values, though both increments add on same amount of mass (40%)[26]. This unexpected non-linear response as a function of weight implies an exponential reduction. It can be theorised that this could be due to the change in morphology of the foot purely as a result of tensing the foot. The arch could flatten and elongate when the foot moves from relaxed position to weight-bearing, as muscles tense to support the weight. This could cause a bigger change in arch shape than when the foot is already tensed to support 50% of the weight and is subsequently required to support more weight without experiencing as much flattening of the arch. Although this observation is based on a single publication and no direct comparison is possible, this difference it is worth noting. Further research would be interesting and required to explore this relation further.

Although one paper[25] stated average AHI values of 0.363 and 0.340, further examination and calculation using numbers provided in the results section found conflicting values. The average AHI-sitting values were calculated to be 0.363, 0.359, 0.366 and 0.358 for the left foot, right foot, men, and women respectively. The average AHI-standing values were calculated to be 0.335, 0.337, 0.344 and 0.333 for the left foot, right foot, men, and women respectively. If these four values were weighted equally, the average would provide an AHI-sitting value of 0.362 and an AHI-standing value of 0.337. These do not correspond to the published values of 0.363 and 0.340 for sitting and standing respectively. As there seem to be inconsistencies in the calculations of the mean AHI values, some caution is warranted when interpreting this data.

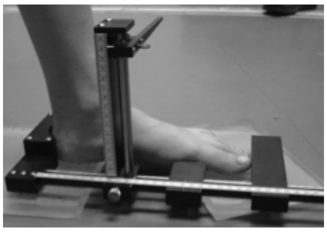

*Figure 3: Adopted image of the Arch Height Index Measuring System[25].*

Various tools can be used to collect the measurements needed to calculate the AHI, for example a ruler, callipers or the AHIMS[8,25] (Figure 3). Accuracy and precision of measurements differ between methods. The use of callipers is said to increase the accuracy compared to the use less specific measuring devices[10]. Additionally, the use of the AHIMS is said to enable a higher intertester reliability. This is due to the consistency in positioning the foot in the device, as opposed to repositioning the handheld callipers with each of the four measurements to be obtained[25].

### *Reliability of arch height index*

The AHI is commonly used and has been well established with various high intratester and intertester reliabilities, depending on the measurement system used. The arch height index was found to be the most reliable and valid method of assessing the arch height[27]. Various publications have stated intraclass correlation coefficients (ICC) for different weight-bearing situations per foot (sitting at 10% weight-bearing and standing at 50% or 90% weight-bearing), these have been compiled into Table 2. M. Razeghi and M.E. Batt (2001) did not publish individual ICC values but did state that the ICC values for AHI-sitting and AHI-standing were inequal[10]. This difference is also observed in the other publications and could be due to inconsistent efforts in altering posture to distribute the right amount of weight. Changes in posture could lead to varying arch heights and therefore varying ICCs.

*Table 2: Overview of published ICC for within-tester reliability (intra) and between-tester validity (inter). A distinction is made between AHI-sitting and AHI-standing values.*
*a 50% weight-bearing, b 90% weight-bearing*

| Publication | Intratester ICC AHI-sitting | Intratester ICC AHI-standing | Intertester ICC AHI-sitting | Intertester ICC AHI-standing | Method |
|---|---|---|---|---|---|
| L.C. Drefus et al. (2017)[8] | 0.8 – 0.82 | 0.84 – 0.87[a] | 0.78 – 0.79 | 0.76 – 0.89[a] | AHIMS |
| M.B. Pohl et al. (2010)[26] | 0.87 | 0.92[a] | N/A | N/A | AHIMS |
| R.J. Butler et al. (2008)[25] | 0.94 | | 0.99 | | AHIMS |
| D.S. Williams et al. (2000)[27] | 0.939 – 0.948 | 0.972 – 0.975[b] | 0.811 | 0.848[b] | Callipers |
| S.P. Shultz et al. (2012)[15] | 0.99 | | N/A | | AHIMS |

The overarching intra- and intertester ICC reliabilities fall between 0.8 – 0.99 and 0.76 – 0.99 respectively. A trend indicating that AHI-standing can be determined with higher reliability than AHI-sitting is observed. A general trend that within-tester reliabilities are higher than between-tester reliabilities was expected; however, this was not observed in AHI-standing by L.C. Drefus et al. (2017) [8] and R.J. Butler et al. (2008)[25].

A guideline to the interpretation of ICC values states that poor reliability is indicated by values less than 0.5, moderate reliability is indicated by values between 0.5 and 0.75, good reliability is indicated by values between 0.75 and 0.9, and excellent reliability is indicated by values greater than 0.9[29]. According to this guideline, both the intratester and intertester ICC values fall in the range of good and excellent reliabilities. The highest intratester reliability was obtained by S.P. Shultz et al. (2012)[15] and the highest intertester reliability was obtained by R.J. Butler et al. (2008)[25]. It is worth noting that that neither paper distinguishes between sitting and standing measurements, which limits the comparability of the data. Both studies utilized the AHIMS to obtain the measurements. Whether these were obtained by trained professionals is not disclosed.

### *Arch height index for children*

The AHI was initially validated and found to be reliable for adults between the ages of 18 to 45 years[25]. Subsequently, a paper tested the reliability and validity of determining the AHI in children aged 6 to 12 years old[8]. The ICCs observed in this study were the lowest reliabilities of those stated above (Table 2). This could be due to difficulty in keeping children static during the measurements which could influence tension in the foot and weight distribution. Regardless of the relatively low ICCs compared to studies with adult subjects, the determination of the AHI in children is found to be of good reliability. S.P. Shultz et al. (2012) investigated the influence of obesity on the structural and functional characteristics of children's feet. An intratester ICC reliability of 0.99[15] was stated for determining the AHI.
As aforementioned, the AHI of a child can be reliably revaluated as the child continues to grow and develop. Children are typically born with flat feet and gradually grow an arch, although a clear consensus is lacking about the age at which this is fully developed[30].

### *Limitations of AHI*

The AHI represents a ratio of measurements that are obtained in a static position to characterize the foot; however, it is questioned whether static measurements can be used to predict dynamic foot function and mobility[18,31–33]. Some research has found evidence showing that static measurements cannot accurately predict dynamic function[18,32]. Contradictory to these findings, other research analysed thirty variables and found AHI-sitting to be one of five main variables (pressure time integral, maximum contact area of medial arch, malleolar valgus index, first metatarsophalangeal joint laxity and AHI-sitting) to predict structure, flexibility and function[12]. Moreover, a significant, but weak, relationship between a higher AHI and a stiffer arch was found, where 9% of the variance in AHI was explained by stiffness[34].
Lastly, the use of measurements in both weight-bearing and non-weight-bearing conditions to assess foot mobility has been proposed[27]. By using measurements of the foot in different weight-bearing conditions, part of the mobility can be considered accounted for.

### 1.1.4. Arch Rigidity Index Ratio

As previously addressed, it is suggested[27] that two weight-bearing situations need to be considered to facilitate commenting on foot mobility. Where the AHI refers to the ratio between dorsum height and truncated foot length within a weight-bearing situation, the arch rigidity index ratio (ARIR) refers to the ratio of AHIs between two weight-bearing situations. This ratio acknowledges the change in arch shape and the ability to maintain the structural arch[15] when transferring from a non-weight-bearing position to a weight-bearing position throughout the gait cycle. With an increase of pressure, a foot flattens and lengthens. This change is quantified when determining the arch rigidity index ratio and describes the relative flexibility of a foot[15].

The ARIR can be determined by calculating the ratio between AHI-standing and AHI-sitting[12,15] (Equation 2).

$$ARIR = \frac{AHI\ standing}{AHI\ sitting}$$

*Equation 2: Arch Rigidity Index Ratio*

The arch rigidity index ratio is expressed as a number between 0 and 1. A higher ARIR indicates a smaller difference between the AHI-standing and AHI-sitting and thus a stiffer arch. A lower arch rigidity index ratio indicates a decreased ability to maintain the longitudinal arch while in a weight-bearing position[15].

Equation 2 has been used to comment on arch stiffness[12] and has been reported to have an ICC reliability value of 0.99[15], demonstrating a high reliability for the ARIR. Using a healthy population of 10 children, the mean ARIR was reported to be 0.95 ± 0.02.

### 1.1.5. Other foot classification methods

*Visual assessment*

One manner of foot classification is visual assessment of curvature, angles and alignment[10]. A subject will sit or stand with their feet on a flat surface and an examiner would observe the foot from one or multiple angles. Although a study from 1991 by L.K. Dahle et al.[6] is referenced in multiple papers[10,35] stating that visual assessment can yield reasonable intertester reliability of up to 71.4%, some hesitance is justified when looking into the details of the study. The assessing clinicians were experienced physical therapists and had attended two 90-minute training courses where specific classification criteria were discussed. Additionally, they performed trial assessments, after which deviating results were thoroughly discussed and followed by a reassessment of the foot. The clinicians were also instructed to only classify a foot pronated or supinated if it showed extreme deviations from a neutral foot type. This lengthy approach is not feasible on a large scale, and therefore not a realistic technique to assess foot type consistently across different institutes.

Another form of visual assessment is the evaluation of photographs. This assessment is proven to be unreliable, as a study published by D.N. Cowan et al. (1994)[36] showed a high variability between trained clinicians, even when classifying extreme foot types. The probability of a clinician classifying a foot in the flattest category after another clinician had already done so ranged from 0.32 to 0.79, with a median probability of 0.57. For the category with the highest arch, probabilities ranged between 0.0 to 1.00, with a median probability of 0.17. Based on their results, this study concluded that objective standards for evaluating foot morphology were required.

An overarching point of caution is raised regarding classifying arch structures through visual methods alone, as the assessments are based on soft-tissue landmarks of the foot. These may not consistently represent the bony structures within the foot[25].
It can be concluded that visual assessment contains many subjective elements and lacks reliability. As it is shown that even trained professionals have different opinions, employing quantitative methods for classifying feet has more potential for consistency for both professional clinicians and research purposes.

### *Radiography*

Radiography, although not a method of classification, is used to facilitate classification through clear imaging of skeletal structures in the foot, which subsequently can be used for measurement of heights, lengths and angles of the bony structures[10]. This visualisation approach can then be used to classify foot types according to the desired classification method. Radiography is commonly reported as being applied to a standing, weight-bearing position[9,10,27], but it is assumed it could also be applied in a lesser or non-weight-bearing position. Successfully using radiography to visualise structures in the foot for classification is often reported to yield high reliability[37,9] and is considered a tool to validate clinical measurements[10].

Despite the high accuracy, this manner of visualisation is not commonly found in research laboratories and clinical environments due to its high price and potentially hazardous nature. This means that justification of this technique is challenging for routine assessments in clinical settings. Additionally, only two-dimensional structures are able to be visualised, which is a limiting factor considering the three-dimensional nature of the foot[10,25].

### *Footprints*

Obtaining footprints by visualising plantar contact area has been used to classify feet into high-arched, normal, or low-arched types[38]. There are several footprint parameters to classify feet, based on various ratios and angles of the contact surface area left by either a static placement or the dynamic placement of the foot. This method is based on the assumption that the print reflects structural components of the foot and changes thereof while the subject stands or moves[10]. This technique is easy, quick and cheap and provides an objective means of measurement[27]. However, M.R. Hawes (1992) performed a study with 115 male participants and concluded that none of five footprint parameters examined were a valid indicator of arch height[39]. It is reported that the soft tissue on the plantar surface of the foot is thick and variable and therefore can obstruct or alter expression of the bony structures in the foot[25,27]. This makes the use of footprints an inadequate method of classifying foot structures.

### *Arch Measurements*

Various measurements relating to the arch height and shape are used to obtain information about the foot structure. Each measurement type aims to achieve foot classification.

The Medial Longitudinal Arch (MLA) (Figure 4) is the arch visualised from the first metatarsal head to the calcaneus via the navicular bone. The arch flattens with the application of weight and is an important structure for shock absorption and momentum when walking[40]. Research into three measurements found to be representative of the MLA (arch length, arch height, and the longitudinal arch angle) has found no significant relationship between static measurements and dynamic motion of the MLA. The conclusion, therefore, was that the MLA is not indicative of the movement of the foot[32]. Despite this research published in 1999, many subsequent studies have continued to investigate classification of the foot through static measurements of the MLA.

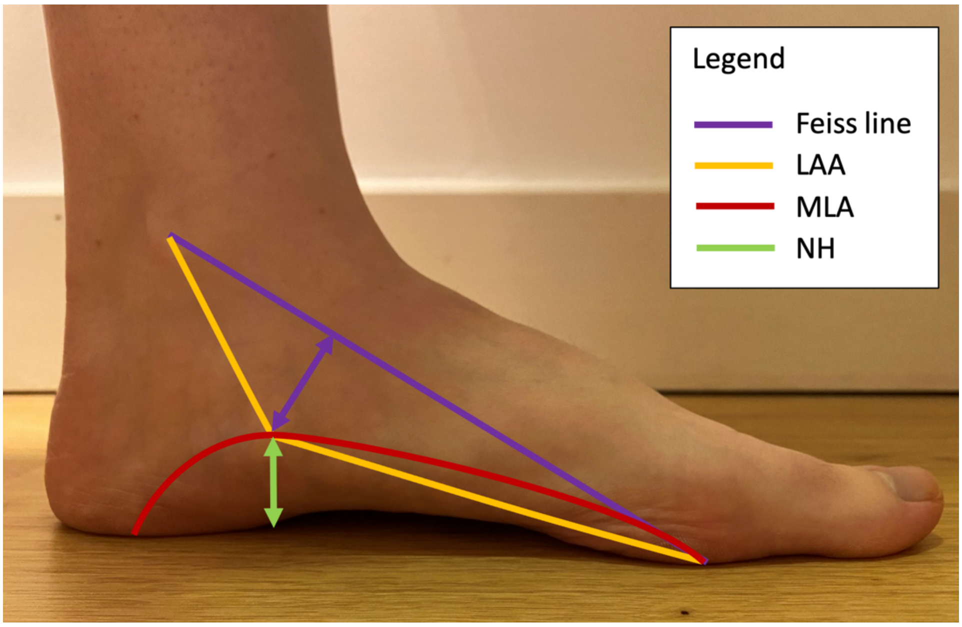


*Figure 4: Image of a foot illustrating the Feiss line, Longitudinal Arch Angle (LAA), Medial Longitudinal Arch (MLA) and the Navicular Height (NH).*

Firstly, the Longitudinal Arch Angle (LAA) has been used to classify foot structure[10]. As is shown in Figure 4**,** a line is drawn connecting the first metatarsal head and the medial malleolus via the navicular tuberosity. The resultant obtuse angle forms the LAA. M.K. Nilsson et al. (2012) report that with a 68% prediction interval, a low arched foot has an LAA of $\leq 130°$; a normal foot has an LAA of $131° – 152°$ and a high arched foot has an LAA $\geq 153°$.

With a 95% prediction limit, a low arched foot has an LAA ≤ 120°; a normal foot has an LAA of 121° – 162° and a high arched foot has an LAA ≥ 163° [1].

Secondly, the Feiss Line, introduced in 1909 by H.O. Feiss[41], consists of a straight line drawn from the medial malleolus to the lowest point of the first metatarsal head (Figure 4). The distance of the navicular tuberosity to the line drawn is said to give information about the arch height, and therefore the strength and efficacy of the arch[41]. H.O. Feiss justifies the choice of landmarks as the navicular bone is susceptible to change in weight bearing, which is said to be important when examining the relationship between these landmarks[41]. The Feiss line can also be used to obtain information about the relative effect of weight bearing on a foot, as the distance can be measured both in non-weight-bearing and in weight-bearing positions. One hundred male gymnast participants were used to take measurements of the Feiss line. On average the navicular tuberosity was found to be 1.24 cm below the Feiss line, with a normal range of 0.64 cm to 1.91 cm. The author states that no reliability must be placed on these figures to use as future reference for typical distribution. Although the paper stresses the importance of methods able to quantify the amount of lowering of the arch, no measures of standardisation were proposed.
Lastly, it must be stressed that statements lacking scientific integrity are found throughout the paper and used as a basis for conclusions, therefore hesitation is urged.

Thirdly, the height of the navicular bone (Figure 4), the highest point of the MLA, can be measured to obtain quantifiable information about the foot structure[10]. M.K. Nilsson et al. (2012) report that with a 68% prediction interval, a low arched foot has a navicular height (NH) of ≤ 3.5 cm; a normal foot has an NH of 3.5 – 5.5 cm and a high arched foot has an NH of ≥ 5.6 cm. With a 95% prediction interval, a low arched foot has an NH of ≤ 2.6 cm; a normal foot has an NH of 2.7 – 6.4 cm and a high arched foot has an NH of ≥ 6.5 cm [1].
An addition to this measurement is suggested by D.S. Williams et al. (2000)[27] where the importance of dividing the navicular height by foot length is elucidated. It is said that the height alone is not an accurate representation of the arch, as differing foot length has implications for the arch structure.
Despite this additional step of critical thinking, the static measurement neglects foot deformation during dynamic behaviour. The range of motion classification method

associated with navicular height is navicular drop. With this method, the height of the navicular tuberosity is measured at non-weight-bearing and at weight-bearing, where the difference is calculated as navicular drop (ND). M.K. Nilsson et al. (2012) report that with a 68% prediction interval, a flexible foot has an ND of ≥ 1.8 cm; a normal foot has an ND of 1.8 – 0.6 cm and a rigid foot has an ND of ≤ 0.6 cm. With a 95% prediction interval, a flexible foot has an ND of > 2.3 cm; a normal foot has an ND of 2.3 – 0.0 cm and a rigid foot has an ND of < 0.0 cm [1].

Although not referenced directly, M.K. Nilsson et al. (2012)[1] support the abovementioned foundational theory by D.S. Williams et al. (2000)[27] that foot length needs to be considered when discussing navicular height. The study performed by M.K. Nilsson et al. (2012) found a significant association between foot size and various MLA parameters, including a linear relationship between foot length and navicular drop among males[1]. This result contradicts earlier research stating that no significant relationship between static measurements and dynamic motion of the MLA could be found[32].

Reliability tests for NH and ND have been performed to comment on the validity of these measures. Clinical assessment of navicular height to foot length ratio is found to correlate closely to radiographic assessment of those structures[42] and therefore has the potential to be a reliable method. The reliability of measuring the navicular height has been reported with intratester ICC values of 0.95 and 0.92 for resting and neutral positions (explained on the following page) respectively, and intertester ICC values of 0.96 and 0.87 for resting and neutral positions respectively[43]. Additionally, intratester ICC reliability values for NH have been reported of 0.977 and 0.982 for sitting position and 0.971 and 0.977 for standing with 90% weight bearing. Intratester ICC values for NH divided by foot length have been reported as 0.971 and 0.980 for sitting position and 0.968 and 0.971 for 90% weight bearing[27]. Adding the foot length as a variable for this measurement reduces the reliability slightly for each measurement, it is also noticeable that the ICC values are lower for the standing position. This could potentially be due to a difference in tensing of the foot between two occasions when balancing the majority of the weight.
Intertester ICC reliability values are reported for NH of 0.924 for sitting position and 0.608 for 90% WB. For NH divided by foot length the ICC reliability value remains consistent for the

sitting position but drops to 0.565 for the 90% WB position[43]. The drop of reliability when assessing 10% WB versus 90% WB is substantial. These mixed results warrant some caution when applying this technique in practice. The same study reported intratester and intertester ICC reliability values for ND of 0.83 and 0.73 respectively[43]. Picciano et al. (1993) investigated the reliability of navicular drop measurements, and reported intratester ICC values of 0.61 and 0.79, and an intertester ICC value of 0.57[44]. The poor reliability is mainly attributed to inconsistent placing of the navicular bone in the neutral position.

The above-mentioned reported reliability values are found to be conflicting, considering that the methodologies are the same. Both studies involve testers manually placing the foot in a neutral position and comparing that to a resting or weight-bearing position. In the study published by K.E. Sell et al. (1994), the ICC value for the resting position (0.95) was only marginally higher than when manually positioned (0.92), although when looking at the intertester outcome, the ICC value drops to 0.87 for the neutral position, compared to the increased ICC value for resting position of 0.96[43]. An explanation for the discrepancy in ICC values between the studies is that the study by Picciano et al. (1993)[44] is performed by two inexperienced physical therapy students, where the study by K.E. Sell et al. (1994)[43] is performed by testers, both with multiple years of experience in the evaluation of biomechanics, but only one having had experience of placing the foot in neutral position. It seems that the difficulty in achieving uniformity in placing the foot in the neutral position is a great contributor to inconsistent results.

In summary, an abundance of conflicting statements surrounding the validity of measurements and concepts of using the MLA to classify a foot into categories are found. For example, the notion that a higher arch improves the efficiency and function of a foot by H.O. Feiss in 1909[41] disagrees with a study performed by Nachbauer and Nigg[18] who investigated the correlation between arch height and arch flattening. They concluded that the amount of vertical deformation of the arch is not affected by the height of the MLA. As previously mentioned, more recent research has since found a weak, but significant, relationship between AHI and arch deformation[34]. Such conflicting views confirm the notion that further, conclusive research needs to be performed.

### *Foot Posture Index*

The Foot Posture Index (FPI-6) is a classification technique consisting of six criteria to be observed in the foot when in a neutrally, balanced standing position[45,46]. Every one of the six criteria is given a score between -2 and +2, where neutral is a score of 0, a negative score represents a supinated foot, and a positive score represents a pronated foot. The foot is observed from various angles and is assessed on alignments within and between both the forefoot and the rearfoot. The method provides a comprehensive method for assessing foot function without the need for any equipment or calculations[47].

Research into the effect of adjustments of foot posture on the FPI score revealed that upon momentarily altering a foot from resting to pronated position, the FPI score did not sufficiently reflect this change. This suggests that not all small movements are represented in the final score and structure assignment following this classification method[48].

Published datasets relating the use of FPI data were analysed and various variables provided by these studies were explored[19]. Although a large sample size was utilized, uniformity of methods between the various studies and their reliabilities cannot be warranted. This comparative study by Redmond et al. (2008) found that the mean FPI-6 score is +4 in the normal adult population, this confirms that a foot at rest is slightly pronated. The lowest value a supinated foot could attain is -12 and the highest value an extremely pronated foot could attain is +12. A normal range of +1 to +7 ($\pm$ 1 SD) is suggested and pathological feet are suggested to have FPI-6 values of < -3 and > +10.

Although valid criticism exists (as discussed above) of visual assessment of the MLA being part of FPI-6, the guidelines alongside the scale and that the six criteria are analysed independently, might diminish the notion that NH or LAA should be included instead[1]. This especially as both of those techniques are not without room for misinterpretation.
The original authors of the FPI method have refined the method to put forth the FPI-6 measure[46]. During this refining, the validity and fit of the final method were reinforced.
An external investigation into the level of agreement between common classification methods[49] found the FPI method to be reliable with an intratester reliability ICC value of 0.93. The FPI-6 method was found to be robust, reliable and valid approach to assessing

static foot structure. However, there appeared to be an inaccuracy in the representation of data regarding FPI-6 classification, hence some caution is warranted when interpreting this data.

Overall, the FPI-6 method of classifying feet seems to be regarded positively. Although the method relies on visual assessment, the clearly specified observational guidelines promote standardisation and are expected to minimise any nonconcurrence. It can be expected that this method used by an experienced analyst would limit misjudgements.

### 1.1.6. The effect of sex, age, weight, and observational side on foot characteristics

The impact of intrinsic factors such as sex, age and weight on foot characteristics has been widely researched, as well as left/right foot and lateral dominance.

The biological sex of an individual is reported not to impact the AHI[25,34,50] or FPI[19] significantly. It was concluded that AHI measurements can be pooled for all genders and the distribution can be disregarded when assessing a mixed gender population[25]. Arch stiffness, however, has been reported to be affected by sex; men exhibited a stiffer arch compared to women[34,50]. Studies evaluating the arch in children aged five to eight years old[51] and ten to fifteen years old[52] found girls to have significantly lower arches than boys. Research assessing boys and girls between the ages of seven and nine years found no significant difference in midfoot peak pressure and maximum force normalized to body weight when comparing between sexes. At the age of 6.9 years old the arch index between boys and girls differed significantly, where boys exhibited a higher arch index (a flatter foot) compared to girls. However, at future assessments around ages eight and nine years this difference had gone[53]. This implies that the MLA is still developing for boys at age 6.9 years, where girls had already reached a stable MLA[53]. This result agrees with the widely accepted principle that infants are born with flat feet and that their MLA fully develops around age five to six[40], also seen in youngest age groups (3 to 4[51] and 3 to 5[54] years old) having the largest proportion of flat feet and experiencing a decreasing prevalence with increasing age, although it seems implausible to ascertain a specific age marker[30]. Contrastingly, it was found that girls experience the most rapid arch height increase between the ages of 10 – 15 years old, whereas boys' fastest increase happens between the ages 12 and 15[52]. The conclusion can be drawn that boys' arch maturation peak occurs slightly later in life. Additionally, FPI scores for minors (aged three to seventeen years old) and elderly (over sixty years old) are reported to be significantly higher than the general population[19].

When comparing younger (mean age 20.9 ± 2.6 years) and older (mean age 80.2 ± 5.7 years) people, it was found that ageing is associated with significant changes in foot characteristics. More pronated feet, a reduced range of motion, and a change in plantar pressure were among the differences found. These differences were hypothesised to be due to a different step length and foot posture[55]. Conversely, it is reported that age does not affect the AHI and arch stiffness (AS) when looking at participants aged 18 to 65[34]. However, when looking at the graphs presented in the study published by R.A. Zifchock et al. (2006) showing the association between AHI/age and AS/age, the trendlines representing the values obtained from the men follow a notable downward gradient compared to the trendlines representing measurements from women which are level for both graphs. The P-values reported for AHI and AS for the women are 0.87 and 0.71 respectively, both with corresponding $R^2$ values of 0.00; it cannot be concluded that their AHI and AS change with age. Contrastingly, the P-values reported for AHI and AS for the men are both 0.07, both with corresponding $R^2$ values of 0.05. The P-values for both variables are much closer to the significant value of 0.05. Thus, although it may not support a statistically significant difference, there is some support for an association between increasing age and a decrease in AHI and arch stiffness for men. Age was found insignificant in the prevalence of flat feet after skeletal maturity when assessing static footprints of participants between the ages of 16 and 56 years old[56].

Research into the impact of weight on foot characteristics has resulted in varying results. No relationship could be established between BMI and FPI; however, the range of BMI represented in the study was not reported[19], which undermines the general applicability of the statement. Additionally, research representing people with a BMI range of 18.2 – 44.0, of which 95% of participants fell within the range of 26.7 – 27.9, showed no relationship between BMI and navicular height, navicular drop, Feiss Line and the LAA[1]. Moreover, a lack of relationship between body weight and navicular height was observed while, conversely, a significant relationship between body weight and arch index was found. However, the probability of soft tissue increasing with body weight and therefore contributing to the plantar surface and affecting the arch index calculation was fortunately considered but not investigated[57].

When foot characteristics of obese and non-obese children (mean age of ten years) were researched, some significant differences were observed. The obese children were found to have less active ankle dorsiflexion, a larger arch drop, and a lower arch rigidity index ratio. No significant differences were observed for morphology parameters. The obese children presented with a more flexible foot in weight bearing and were hypothesised to have increased foot contact in the stance stage during gait[15]. A higher prevalence for flat feet with obesity (BMI $\geq$ 24) was also found in an adult population[56]. Although a trend was observed between a lower arch and an increase in body weight, the relevance of weight on arch height was diminished with age (population between the ages of seven and fifteen years old) and increased physical activity[52].

Foot characteristics between the left and right feet have previously been compared and have shown no significant difference in arch height flexibility (adults)[7], arch index, midfoot peak pressure, or maximum force (children)[53]. Although significant differences were found for the LAA and FL (adults), these did not impact the cut-off values to categorize the MLA into arch heights, so the difference was considered clinically insignificant[1]. Conflicting results have been reported regarding the uniformity of AHI values between the left and right foot. Both a statistically insignificant difference ($P = 0.3$) has been reported (adults)[25] as well as statistically significant differences for AHI ($P < 0.003$), dorsum height ($P < 0.018$), and truncated foot length ($P < 0.047$) between lateral sides. No statistically significant differences were observed between the left and the right total foot length for adults ($P > 0.442$)[28]. Both studies have similarly sized populations of n = 100[25] and n = 79[28] and use the same equipment (AHIMS). However, as discussed in section 1.1.3., some inconsistencies seem to be present in the mean AHI values reported[25]. It cannot be certainly stated which values were used to calculate the P-value and if any inconsistencies would reflect on the P-value or decrease its validity. Nevertheless, despite noted discrepancies, they were not large and unlikely to have sufficient impact to change the P-value from 0.3 to < 0.05.
Comparing foot characteristics between lateral dominance and non-dominance, it was found that arch stiffness was not different between sides, but the AHI was higher for the dominant foot (adults)[34]. This is an interesting result and prompts the hypothesis that the study observing a significant difference between left and right feet[28] may have had a skewed population towards right foot dominance.

### 1.1.7. Environmental impact on foot characteristics

When investigating a possible relationship between terrain and foot characteristics, although papers are scarce on this topic, a statistically significant lower arch height was found in Polish participants living in urban areas than in rural areas[52]. However, explanations on how these areas are defined is missing. More environmentally focussed, J.J. Echarri and F. Forriol (2003) explore the relationship between footprint morphology and the type of Congolese terrain. However, the use of footwear is dependent on the terrain type: children in rural areas predominantly do not wear shoes and children in urban areas predominantly do wear shoes. The general trend reported shows a greater proportion of flat feet in the urban environment where wearing shoes was typical (including some statistically significant outcomes, depending on age bracket and test employed). Two opposite conclusions are published: footwear is a causative factor of flat feet, and footwear has little influence on the morphology of the foot[51]. Although the second conclusion was generally stated, it seems to discredit the theory that different arch heights between girls and boys are due to generalised footwear habits, as the same trend is also observed in children who mainly live barefoot. Hence the influence of footwear on the greater proportion of flat feet observed in urban terrain is unclear. Ultimately, this research does not isolate the terrain as a variable and conclusions cannot be extrapolated to populations where similar footwear habits are exhibited between varying terrains.

Other research investigated two Colombian populations with varying footwear habits, racial characteristics, and climates to find flatter feet in the city of Bogotá compared to the city of Barranquilla[54]. The actual terrain seems to be similar between the two cities and a clear conclusion on which variables are causative of this observation is again lacking.

Research directly focussed on the effect of footwear on foot characteristics finds flatter feet in children that wear footwear for over eight hours a day and in children that wear shoes before the age of six years[56], as well as the conclusion that wearing closed-toe footwear is associated with a lower MLA[53].

All in all, the effect of terrain and environmental factors on foot characteristics is not clear based on the available literature.

### 1.1.8. Gait

The process of walking is made up of repeated gait cycles; a general understanding of these is needed as different phases influence the movements of the foot.

The gait cycle is divided into two phases: the stance phase, during which the foot is grounded, supporting the bodyweight as it moves from the heel to the toes; the swing phase, which is initiated as the foot comes off the ground.

The stance phase occupies approximately 60% of the gait cycle and is subdivided into three phases: the contact phase, where the heel contacts the ground; mid-stance, where the foot flattens as the bodyweight moves forward and is followed by the heel lifting off the ground; propulsion, where the toes push off to complete the stance phase.

The swing phase is characterised by the acceleration of the lower limb as a result of propulsion; upon mid-swing the leg reaches a constant velocity and subsequently decelerates as it lowers to the ground to initiate the stance phase again[20].

Double stance occurs briefly when the stance phases of both legs overlap, and the body is supported by both feet simultaneously.

Gait patterns can be assessed by measuring parameters such as step and stride length, cadence, stance and swing phase times, double support time, step time and full gait cycle time[11,14]. These variables can be used to understand differences in dynamic foot function among foot types[13].

## 2. The influence of terrain on Foot Flexibility

In this study, analyses of previously collected datasets are performed, with the aim to elucidate the relationship between the terrain an individual grows up on and the structure of their developing foot as represented by their Foot Flexibility (FF). As certain foot characteristics are associated with a higher propensity for certain injury types, knowing if, how and to what extent terrain plays a part in flexibility, interventions can be formulated to address the problem at the source before injuries occur. This could increase overall well wellbeing and prosperity, saving both healthcare and society time and money.

This chapter discusses the data collection, analyses, and conclusions of the Preliminary Dataset (sections 2.1.1 and 2.2.1.) and the BBC Dataset (sections 2.1.2 and 2.3). The Preliminary Dataset yielded 162 datapoints in total collected by participants and by a researcher. This allowed for comparison between the two measuring parties.

The data discussed in this chapter was collected through a collaboration with the BBC's UK-wide initiative 'Terrific Scientific'. Terrific Scientific consists of curriculum-linked science aimed at pupils between the ages of nine and eleven years to encourage scientific enquiry[58]. Schools can choose to partake in projects and follow a lesson plan to ultimately add data to an interactive map, this adds the ability of schools to compare their results with other participating schools. The project 'Fantastic Feet' was a part of the Terrific Scientific curriculum in the academic year of 2017/2018 resulting in the participation of approximately 200 schools.
The resultant BBC Dataset yielded a total of 356 datapoints collected by participants which were assessed and analysed. The relationship between terrain and Foot Flexibility is explored. The terrain is categorized as Natural, Developed or Mixed. Foot structures are differentiated through differences in Arch Rigidity Index Ratio (ARIR) (section 1.1.4) between feet. ARIR was renamed as 'Foot Flexibility' for the participants and will be used henceforth.

It is hypothesized that the Foot Flexibility values collected will display a bimodal distribution. Individuals growing up on a natural and more irregular terrain are expected to have more flexible feet to accommodate unevenly distributed force. Those growing up on a more developed terrain are expected to need to compensate less for uneven forces and consequently have more rigid arches. Therefore, feet adapted to Natural terrain are expected to form a peak around the lower end of the Foot Flexibilities range, while feet adapted to Developed terrain are expected to form a peak with higher FF values.

## 2.1.Methodology

### 2.1.1. Preliminary data collection

The Preliminary Dataset was collected to refine the experimental design and instructions to be provided to schools participating in the Terrific Scientific initiative and to define FF bins to enable categorisation and comparison of data. Three schools were selected by the BBC as a representation of demographic within the set-out terrain classifications; data collected from these schools were combined to form the Preliminary Dataset.

Researchers visited the three schools and collected data with the participants after introducing the research and providing instructions for data collection. Participants paired up and measured each other's feet as explained by the researchers and recorded their results alongside their counterpart's participant number and age. One researcher also measured the participants' feet, which results were noted alongside the participant number. The full length of the foot, the dorsum height and the truncated foot length (TFL) were measured. These measurements were collected for both feet in both standing and sitting position using A4 paper, a pencil, and a ruler for the participants and callipers for the researcher. All results were recorded and collected per school and subsequently analysed (section 2.2.1).

### 2.1.2. BBC data collection

Between October 2017 and January 2018, participants aged nine to eleven years from participating UK schools measured their feet as part of the BBC science programme Terrific Scientific. Teachers received an information pack (consisting of a teacher resource: Appendix 1a and a student worksheet: Appendix 1b) to educate the participants on foot flexibility, terrain and measurement taking. The participants were asked to stand with their weight equally divided over both feet with their left foot on an A4 paper. A second participant drew a line at the back of the heel and the top of the longest toe (Figure 5), using a pencil and a ruler. The distance between both lines was measured and the midpoint was calculated, where another line was drawn. The height of the foot at the midpoint was measured (Figure 6). Lastly, a ruler was slid underneath the toes of the standing participant until it reached the ball of the foot (first metatarsophalangeal joint) (Figure 5), and another line was drawn. The distance between the heel and this line (TFL) was measured. The participants took the same measurements with the same participant sitting on a chair, with their knees bent at a 90° angle.

It is important to note that as these measurements were obtained with only the supervision of a teacher informed by online instructions, adherence to the methodology cannot be guaranteed. The participants used these measurements to calculate their arch height index (AHI) for both sitting and standing position (Equation 1, reproduced below for convenience), and subsequently their Foot Flexibility (Equation 2, reproduced below for convenience). The results could be uploaded as an individual value or as the class modal bin to an online data collection questionnaire. The class mode was determined by which bin (section 2.1.4) had the highest number of individual values per class.

Alongside the individual measurements, AHI and FF results, the participants were asked to record their age, gender, school's postcode, and whether they spend more time on man-made or natural terrain. Additional questions were posed, and answers collected (Appendix 2), which are not within the scope of this thesis and thus not discussed.

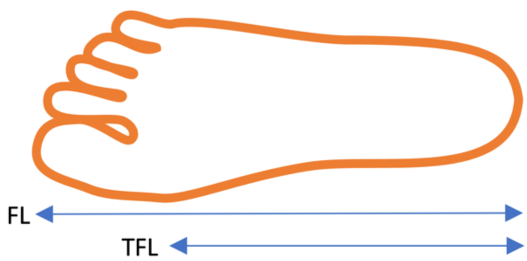


*Figure 5: An illustration representing plantar surface area including the foot length (FL) and truncated foot length (TFL).*

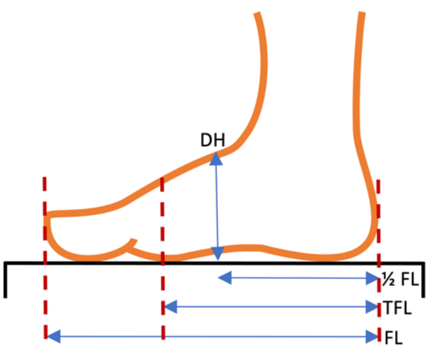


*Figure 6: Side view diagram of a foot illustrating the dorsum height (DH), foot length (FL), truncated foot length (TFL) and a half foot length (1/2 FL).*

$$AHI = \frac{Dorsum\ height}{Truncated\ foot\ length}$$

*Equation 1: Arch Height Index (reproduced)*

$$Foot\ Flexibilty = \frac{AHI\ standing}{AHI\ sitting}$$

*Equation2: Foot Flexibility (reproduced)*

The dataset collected through the Fantastic Feet project run through the BBC Terrific Scientific initiative will from here on be referred to as BBC Dataset.
This nationwide project yielded a total of 150 data points for individual students, 203 data points from teachers – class modal bins – and 3 datapoints from students concerning a measurement from a peer in their surroundings. The last three datapoints were included in the individual dataset. The Individual Foot Flexibilities (n = 153) were reported as numerical values and class data was reported as the most commonly occurring FF bin in that class (section 2.1.4).

All collected data was sorted and separated into Individual values and Class bins and the FFs were grouped per terrain per classifying party (section 2.2.4). The Individual FFs were grouped into their respective bins. The Error Correction Calibration (section 2.2.2) was applied to the Individual Dataset and the calibrated data was grouped as above (Appendix 3). Lastly, the data was organised per sex and age. Outliers < 0.4 and ≥ 1.1 were removed for all analyses.

### 2.1.3. Postcode allocation

As well as participants classifying their school's postcode as natural or man-made, the researcher classified postcodes as Natural or Developed, which allowed for comparison of FFs between the two terrains and allowed for subjectivity and relative objectivity to be separated during the analysis process. Google Maps was used to interpret terrain by postcode by the researcher. A more in-depth discussion of this process can be found in section 2.2.3.

### 2.1.4. Data processing and mathematical tools

Foot Flexibility values obtained from the Preliminary Dataset were used to create bin structures that could be used to group FF values from the BBC Dataset to enable comparison of individual datapoints with the class data and additional analysis. These predetermined bins were: < 0.700; 0.700 – 0.749; 0.750 – 0.799; 0.800 – 0.849; 0.850 – 0.899; 0.900 – 0.949; 0.950 – 1.000 and were provided in the BBC information pack. The lower limit was chosen to represent unlikeliness based on the Preliminary results and the upper limit represents anatomical restriction.

Excel was used to re-calculate the AHI and Foot Flexibility for the datapoints collected by the participants in both the Preliminary Dataset and the BBC Dataset. Excel was also used for other simple calculations and non-statistical data comparison. The Shapiro-Wilk test was employed in POSIT Cloud (previously R-studio cloud)[59] to determine if data was normally distributed. Statistical analyses following the Shapiro-Wilk test were chosen according to guidelines[60].

Sub-populations used in comparisons were determined according to areas of interest by combining variables from each category row presented in Figure 7. The Wilcoxon test (rank-sum and two-sided, unless otherwise stated) and the Chi-Squared test were applied to determine if two sub-populations were significantly different in POSIT Cloud as well. The Wilcoxon test was applied to Individual values and compares the median between the two sub-populations compared, providing an indication whether the two sub-populations have statistically different medians. The Chi-Squared test was applied to binned Class data and compares the distribution among the bins between the two sub-populations. The alpha value of 0.05 is used to indicate statistical significance for all statistical tests.

Analysed data are presented in separate sections per investigated sub-population supplemented with tables and figures where appropriate. The results exclusively relate to FF values with the exception of one section where the legitimacy of using Foot Flexibility as a measure is illustrated through comparing AHI values (section 2.3.3). The results and corresponding P-values presented in the main text are limited to relevant data for the discussion of the research question; a full overview of calculations performed, and results can be found in appendices signposted throughout the text.

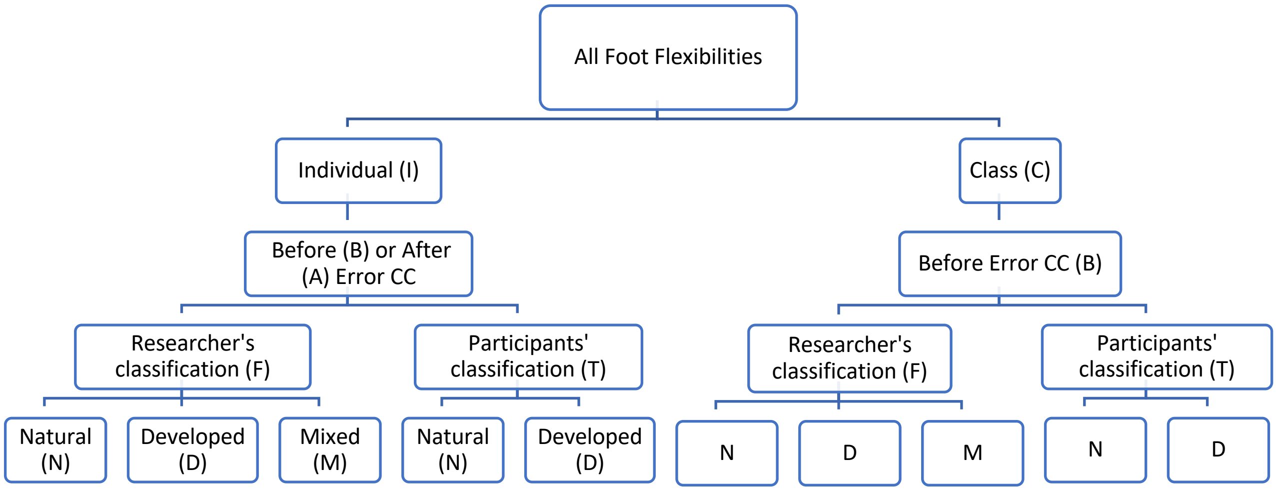


*Figure 7: A diagram illustrating the composition of sub-populations used in comparative statistical tests including the abbreviations used to analyse and discuss the BBC Dataset. Individual (I), Class (C), Researcher's classification (F), Participants' classification (T), Natural (N), Developed (D), Mixed (M), Before Error CC (B), After Error CC (A).*

## 2.2. Development and Analysis

The initial analysis approach was refined through developmental decisions based on preliminary data examination: analysis of the Preliminary Dataset revealed the need for an additional calibration step during analysis of the BBC Dataset; classifying the postcodes illustrated the need for an additional terrain category; and the values obtained in the BBC Dataset showed an omission in the bin range as determined using the Preliminary Dataset. The developmental process and decisions leading to final analyses is discussed.

### 2.2.1. Preliminary Dataset

The data making up the Preliminary Dataset was collected at three participating schools, termed A, B and C. Foot length, truncated foot length and dorsum height were measured for the left and right foot in both sitting and standing position. For each set of measurements, it was logged whether these were collected by a participant or by the researcher. The arch height index (Equation 1) and the Foot Flexibility (Equation 2) were calculated, and averages of these can be found in Appendix 4. Using AHI and FF as measures based on data taken by participants in the age range of 9 – 11 was considered to be the most transferrable and does not present many opportunities for significant losses to accuracy. As previously mentioned, (section1.1.3) the AHI-standing can be calculated using either 50% weight-bearing (WB) or 90% WB. For the purposes of this study, 50% WB was utilised. It was considered that 90% WB would require more time and tools and increase the level of difficulty for the participants. Additionally, the arch deformation from 10% WB to 50% WB is sufficient to calculate the AHI and subsequently the FF. The additional effort of using 90% WB for the possibility of clearer results was deemed unnecessary, as one study[26] reported values for both 50% WB and 90% WB, after which it could be observed that the AHI only changed an additional 1/10$^{th}$ going from 10% WB to 90% WB compared to the difference between 10% WB to 50% WB.

The Foot Flexibilities were sorted into bins as described in section 2.2.4 and FFs based on the researcher's classification. The distribution of Foot Flexibilities is visualised for left and right feet separately in Figure 8 and Figure 9, respectively. Firstly, these figures show that FF values differ depending on the expertise of the person carrying out the measurements. The extent of the discrepancy between measurements has mostly led to results falling into different bins. Secondly, from Figure 8 and Figure 9, it can be inferred that the majority of the FFs fall in the bins 0.800 – 0.849 and 0.850 – 0.899. This shows a distribution of FFs around the median of the expected ranges. Moreover, Figure 8 andFigure 9 demonstrate that the majority of FFs resulting from participant measurements (85% left foot, 79% right foot) falls within the expected range of 0.700 – 1. Outliers could potentially be due to inaccurate measuring tools, imprecise adherence to method, inexperience, and/or uneven shifts of weight on the foot being measured. Only 5% and 4% of the researcher's measurements resulted in outliers for the left and right foot respectively. As the majority of FFs falls within the expected range and is centred around the median bins, it appears the bin determination was made correctly, although the Preliminary population is not substantial enough to state this with certainty.

Upon initial observation, the left and right feet appear to have different FF distributions, partially due to the high number of outliers (Figure 8 and Figure 9). This apparent discrepancy is observed in the participants' measurements, but not in the measurements taken by the researcher: the average FFs for the left and right feet measured by the researcher are 0.858 (SD = 0.060, n = 38) and 0.859 (SD = 0.050, n = 52) respectively; the average FFs for the left and right feet measured by the participants are 0.884 (SD = 0.11, n = 35) and 0.942 (SD = 0.14, n = 37) respectively (Table 5). However, when performing statistical analyses (section 2.3.2), the seemingly observed difference between left and right feet was found statistically insignificant (for both the researcher's measurements (P = 0.801) and for the participants' measurements (P = 0.151)). The similarity between left and right Foot Flexibilities is substantially larger for the researcher's data, as illustrated by the similar average and smaller standard deviation. This similarity between left and right Flexibilities allowed refining of the BBC data collection method to include only one foot for measurement, with the added benefits of saving time and keeping the research focussed. The decision to analyse only one foot is supported by research[61] urging the analysis of 'people' as opposed to their feet, suggesting that using paired data can potentially lead to questionable outcomes.

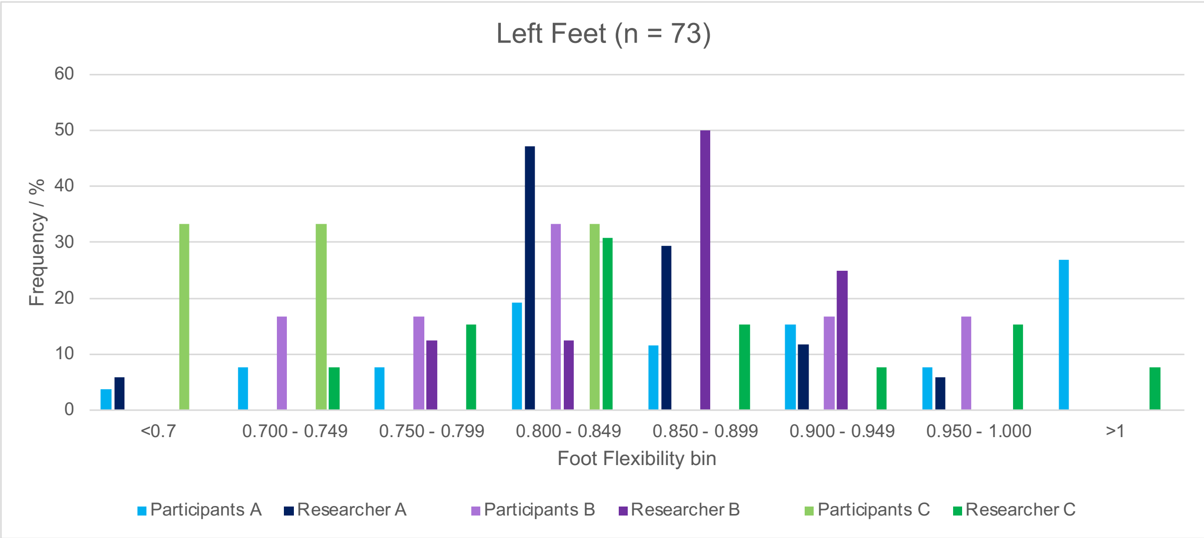


*Figure 8: Distribution of all Foot Flexibilities (including outliers) per school (A: blue, B: purple, C: green) obtained by the participant (lighter shade) or the researcher (darker shade). Frequency as a percentage per measuring party are plotted against binned FFs. A: participants n = 26, researcher n = 17; B: participants n = 6, researcher n = 8; C: participants n = 3, researcher n = 13.*

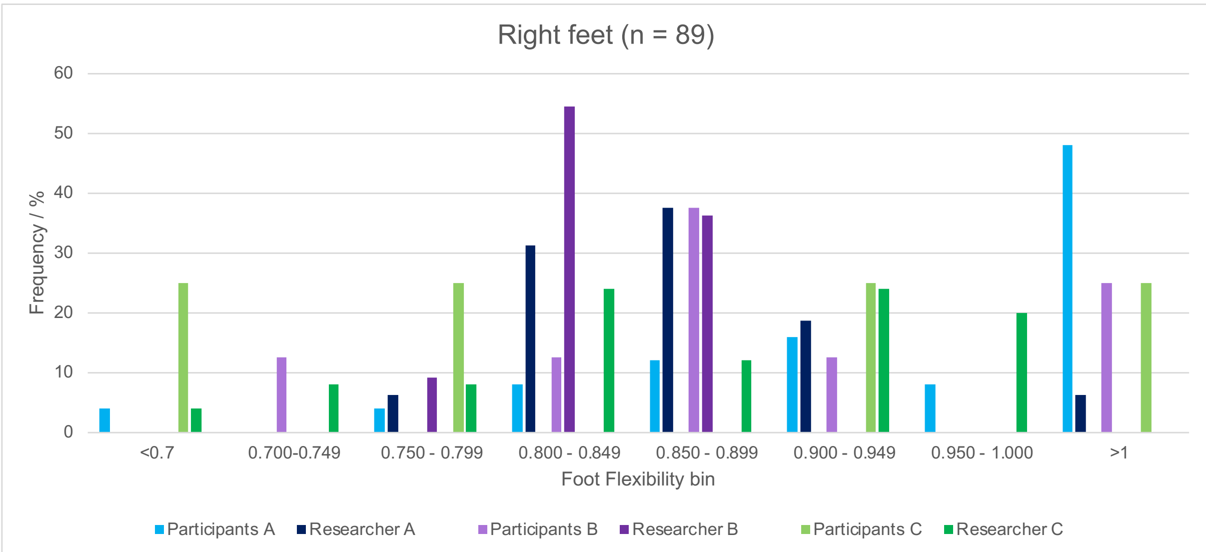


*Figure 9: Distribution of all Foot Flexibilities (including outliers) per school (A: blue, B: purple, C: green) obtained by the participant (lighter shade) or the researcher (darker shade). Frequency as a percentage per measuring party are plotted against binned FFs A: participants n = 25, researcher n = 16; B: participants n = 8, researcher n = 11; C: participants n = 4, researcher n = 25*

When observing only feet that were measured by both a participant *and* a researcher, it was noticed that the majority of results differed enough to fall into separate bins (Table 3 and Table 4). Participant outliers were included to aid visualisation and comparison of measurement discrepancies in full, the researcher's outliers (> 1.0) were excluded to limit comparison to valid controlled measurements.

*Table 3: The frequency of bin differences observed per school between the researcher's calculated FFs and the participants' calculated FFs for the left foot*

| Bin difference | | 0 | 1 | 2 | 3 | 4 | 5 | 6 | Total n |
|---|---|---|---|---|---|---|---|---|---|
| Frequency observed | School A | 3 | 4 | 4 | 4 | 1 | - | - | 16 |
| | School B | 1 | 1 | 3 | 1 | - | - | - | 6 |
| | School C | - | - | - | 2 | - | 1 | - | 3 |

*Table 4: The frequency of bin differences observed per school between the researcher's calculated FFs and the participants' calculated FFs for the right foot*

| Bin difference | | 0 | 1 | 2 | 3 | 4 | 5 | 6 | Total n |
|---|---|---|---|---|---|---|---|---|---|
| Frequency observed | School A | 3 | 1 | 4 | 4 | 2 | - | - | 14 |
| | School B | 1 | 1 | 2 | 0 | 1 | 1 | - | 6 |
| | School C | 1 | - | - | - | 1 | 1 | 1 | 4 |

From a combined total of 49 feet measured by both parties, nine results fell into the same bin, seven into neighbouring bins, thirteen into two bins away, eleven into three bins away, five into four bins away, three into five bins away and one into six bins away. These quantised differences illustrate the wide range of mismatched results between the participants and the researcher and signify the need for corrective measures (section 2.2.2).

### 2.2.2. Error Correction Calibration

Results from the Preliminary Dataset were analysed, and discrepancies and errors were visualised and used to establish trends. The discrepancy between values measured by participants and the more reliable values obtained by a researcher demonstrated the need for caution when analysing data based on participant measurements. To visualise the precise extent of the discrepancy, the average discrepancy per lateral side was calculated (Table 5), only taking feet that were assessed by both measuring parties into consideration. The average Foot Flexibility according to the researcher's measurements is 0.857, the average FF according to participant measurements is 0.900, and the average discrepancy percentage is 4.77%.

*Table 5: The average FFs and the discrepancy percentage of feet analysed by both the researcher and participants from the Preliminary Dataset. The discrepancy percentage represents the percentage of the participants' result that is erroneous.*

| | **Average Foot Flexibility** | |
|---|---|---|
| | **Left Foot** | **Right Foot** |
| Researcher's measurements | 0.855 (n = 25) | 0.860 (n= 26) |
| Participants' measurements | 0.869 (n = 25) | 0.930 (n= 26) |
| Discrepancy percentage | 1.66% | 7.56% |
| Average discrepancy percentage | 4.77% | |

It is apparent that the participants' outcomes are skewed to larger values. The results obtained by the researcher were considered the baseline of valid measurements, against which the participants' results were compared. The discrepancy percentage (Table 5) was calculated as the difference between the researcher's average outcome and the participants' average outcome divided by the participants' average outcome (Equation 3a) (for example (0.869-0.855)/0.869 for the left foot). Thus, the magnitude of the discrepancy percentage in participants' values was determined.

The discrepancy percentage observed for the right foot (7.56%, Table 5) motivated statistical analysis to check the significance of the discrepancy. Paired T-tests revealed statistically significant differences between the means reported by the researcher and the participants for the overall values ($P = 0.039$) and right feet ($P = 0.036$), but not for left feet ($P = 0.554$). Moreover, a one-sided test showed the participants' outcomes to be significantly greater than the researcher's for the overall values ($P = 0.020$) and the right feet ($P = 0.018$).

Illustrated by the skewed data reported by the participants, imprecise measuring and/or recording of the participating demographic appears to yield unreliable data. The established significance of discrepancy warranted the development and implementation of a systematic measurement error correction for data gathered by participants.

The correction factor was determined using the average reported values of feet measured by both measuring parties (Equation 3b), resulting in the Error Correction Calibration (Error CC) value of 0.9523. Using Equation 3c, the participants' data could be calibrated to return the baseline values determined by the researcher. Aiming to lower the values reported by the participants accordingly, multiplying their result by the correction value (Equation 3c) resulted in the overall distribution getting nearer the researcher's distribution of calculated FF values. A T-test comparing participant values After Error CC to the researcher's values provided a P-value of 0.958, indicating the efficacy of the calibration in minimising the gap between the measuring parties in comparison with the P value of 0.039 Before Error CC. Although the discrepancy between values calculated for the left feet were not statistically significant, it was decided to apply the Error CC to all BBC Individual datapoints to compensate for the general methodical error of the participants.

$$\underbrace{Calibrated\ FF\ value = FF_{Participant} \underbrace{\left(1 + \underbrace{\frac{FF_{Researcher} - FF_{Participant}}{FF_{Participant}}}_{a}\right)}_{b}}_{c}$$

*Equation 3: a: discrepancy percentage, b: correction factor, c: full equation used to calculate the calibrated FF value*

The average error percentage was found to be 4.77% yielding the Error CC factor of 0.9523. This error correction was applied to all individual datapoints of the BBC Dataset to account for the anticipated inaccuracies in measurements and calculations performed. The absolute FF results were multiplied by 0.9523, lowering the result. Consequently, some high FF values that were originally considered outliers now fell into a bin of expected flexibilities. Similarly, other lower FFs were lowered further and became outliers. As the correction is expected to improve accuracy, these changes were accepted.

As the Error CC can only be applied to individual numerical values, the class data cannot be calibrated and is accepted as originally reported. Regardless, the class data is expected to need less calibration as the modal FF bin is reported, and so individual values changing, and potentially changing bin is expected to have minimal impact. Statistical analysis of the effect of the Error CC to the BBC Dataset showed a statistically significant impact (Wilcoxon signed-rank both one- and two-sided: P < 2.2e-16) (section 2.3.4), thus justifying its application.

### 2.2.3. Postcode classification

Participants classified the terrain that they, either individually or as a class, spent the most time on as man-made or natural. The term man-made was changed to 'Developed' for the analysis.

Literature establishing clear guidelines to classify terrain could not be found, so postcodes submitted by participants were entered into Google Maps and viewed using satellite view by the researcher to classify the terrain. The participant's classification was not looked at prior, ensuring the decisions were made unbiased. Terrains were initially classed as Developed or Natural, based on the amount of greenery observed. Street View was used intermittently to determine whether green areas found on the satellite view represented fields, or woodland or a developed area with many trees planted along the streets. Where the majority of the satellite view would show greenery, the postcode would be classified as having a predominantly Natural terrain. The size of the urban area and the vicinity of fields surrounding the postcode were taken into consideration. The presence and size of gardens were also taken into consideration. It was assumed that participants living in houses with big gardens would spend more time on natural terrain, despite living in a more developed area than participants living in a similarly developed area, but in houses without gardens.
Big cities were classed as having predominantly Developed terrain.

A website[62] was used to visualise a thirty-minute car-ride radius from the postcode; this was an approximate estimate for a maximum reasonable commute for primary school. A statistic from 2014 by the Department for Transport[63] reported an average travel time of 13 minutes for primary school children. The 30-minute radius includes the ~15-minute travel to school and a 15-minute journey the opposite way for leisurely activities. The area within this thirty-minute radius was taken into consideration for terrain classification. The website showing the radius was used for the first ~15 – 20 postcodes, but this was later estimated.

It became clear that there was a need for a third category; the Mixed category was introduced for terrain with a more similar distribution of Developed and Natural surfaces. The Mixed category is available solely for the researcher's classification as this was only introduced after interpreting the data provided by the participants.

A log was kept with the postcode, the researcher's classification, a screen capture of the terrain on Google Maps and a short justification for the classification. An example of this can be found in Appendix 5. The 153 Individual data points resulted in thirteen different postcodes to be analysed and 170 different postcodes from the 203 Class data points. This means that thirteen schools provided participants with computers to upload their individual measurements, whereas 170 schools provided class averages. This distribution may influence the analyses presented later.

The 153 Individual data points originating from thirteen postcodes were assigned as 75% (115/153) Natural terrain, 1% (1/153) Developed terrain and 24% (37/153) Mixed terrain by the researcher. The participants assigned these FFs to have 45% (69/153) Natural terrain and 55% (84/153) Developed terrain. Only 33% (51/153) of postcodes were assigned the same classification by both the participants and the researcher. Due to the low number of Developed classified terrains by the researcher, Mixed and Developed classifications were combined to yield a 45% (69/153) similarity (discussed further in section 2.4). Out of the 203 Class datapoints included in the 170 postcodes, the researcher classified 49% (100/203) as Natural, 18% (36/203) as Developed and 33% (67/203) as Mixed terrain. The participants classified 16% (33/203) as Natural terrain and 84% (170/203) as Developed terrain. A similar proportion of 30% (61/203) of the postcodes were assigned identically, increasing to 61% (124/203) upon combining Mixed and Developed classifications.

As shown above, the addition of the Mixed to the Developed postcodes increases the percentage of uniformly assigned postcodes. However, of the 37 Individual Mixed postcodes, only 18 correspond with participants' classified Developed postcodes. This ~1:1 ratio suggests that the Mixed category is an equal representation of Natural and Developed terrain and the increase in uniformly assigned postcodes with the addition of Mixed to Developed is due to chance.

The overlapping proportion is much higher for the Class Mixed postcodes, where 63 of the 67 Mixed postcodes overlap with participants' assigned Developed postcodes. This would suggest that the Mixed category is indeed more consistent with the Developed category.

All in all, the distribution of assigned postcodes appears to vary between the assigning parties, which is confirmed with statistical analysis (section 2.3.7). It is taken into consideration that the participants may not necessarily spend most of their time outside of school on the terrain that is most apparent in their area, some discrepancy is expected to arise from this nuance.

### 2.2.4. Changing of the Bins

The bins to categorise Foot Flexibility values were determined to be < 0.700; 0.700 – 0.749; 0.750 – 0.799; 0.800 – 0.849; 0.850 – 0.899; 0.900 – 0.949; 0.950 – 1.000 based on data obtained in the Preliminary Dataset. Despite the median-centred distribution of Preliminary FFs, 42% (n = 64) of BBC Individual datapoints were outliers with 18% (n = 27) falling below the expected range. New bins to include a lower range were introduced for the analysis of Individual datapoints of the BBC Dataset. The bin < 0.700 was replaced by 0.400 – 0.499; 0.500 – 0.599; 0.600 – 0.649 and 0.650 – 0.699; subsequent bins remained unchanged, but an additional bin was devised for FFs between 1.001 – 1.099.

Bins on the lower end of the spectrum were extended more extensively than the higher end because an FF of > 1.0 is more clearly physiologically unlikely as that would imply that the foot would adopt a rounder shape with the application of weight. The large number of > 1.0 FF outliers is expected to originate through erroneous measuring and collecting of data which follows the trend observed in the Preliminary Dataset where participants generally provided higher outcomes.

The bins for Class data could not be extended as the modal bin was already reported based on the bin selection provided in the information pack. The lowest bin (< 0.700) was reported for 6% (n = 12) of the Class data, which also implies that the accommodation of bin extension was less necessary. The large difference between number of outliers observed in Individual and Class data prompts the question of whether more supervision was present during the measuring and reporting for the Class data than for Individual data.

### 2.2.5. Abbreviation interpretation

Abbreviations are used throughout this chapter, refer to Table 6 for a full list of abbreviations.

'Individual data' (I) refers to FF datapoints submitted for individual participants. 'Class data' (C) refers to the FF bin that was most represented in a particular school class. 'Natural terrain' (N) and 'Developed terrain' (D) represent the terrain type that was allocated to a particular postcode by either the 'researcher' (F) or the 'participants' (T) (e.g., FN represents values originating from a terrain classed Natural by the researcher and TD represents values originating from a terrain that a participant classed as Developed). 'Mixed terrain' (M) Flexibilities are occasionally combined with Flexibilities from Natural or Developed terrain when classified by the researcher. Throughout the text this fusion will be denoted as 'Natural + Mixed' or 'Developed + Mixed', in the abbreviated data description, the two letters are written without the + sign (e.g., NM, DM). The acronym for 'Before Error CC' (B) refers to datapoints without having accounted for the participants' systematic measurement errors. 'After Error CC' (A) refers to FF values to which the Error CC has been applied. As the Error Correction Calibration cannot be applied to Class data, for consistency the B will still be assigned to calculations referring to class data. Lastly, for some analyses the Individual and Class data were combined (Individual + Class), in which case the 'I' or 'C' is missing from the abbreviated sub-population description. Depending on whether the Error CC has been applied to the Individual data, the A or B at the end of the abbreviation will change.

An example of how abbreviations are used to form sub-populations: CFNB refers to FFs from the Class dataset (C), of which the postcode was classified by the researcher (F) to represent a Natural terrain (N) before application of the Error CC (B).

Acknowledging that Individual data has bins ranging from 0.400 – 0.499 to 1.000 – 1.099 and Class data has bins ranging from < 0.7 to 0.950 – 1.000, when combining Individual + Class data, these bins were merged to represent the combined data most comprehensively. The I + C combined range of bins was 0.400 – 0.499 to 0.950 – 1.000. All Individual values > 1.000 were excluded, and the Class bin frequency of < 0.7 was added to 0.650 – 0.699. No further bin alterations were made.

*Table 6: Abbreviations used to analyse and discuss the BBC Dataset.*

| Individual data | Class data | Researcher classification | Participant classification | Natural terrain | Developed terrain | Mixed terrain | Before Error CC | After Error CC |
|---|---|---|---|---|---|---|---|---|
| **I** | **C** | **F** | **T** | **N** | **D** | **M** | **B** | **A** |

## 2.3. Results and statistical analysis

Key results from analysis of the Preliminary Dataset and the BBC Dataset are presented below. Calculations that have yielded statistically significant outcomes (P-value < 0.05) are set out below and are discussed in section 2.4. When the P-value < 0.05, the null hypothesis (no significant difference between the (sub-)populations) is rejected. Accordingly, the alternative hypothesis is accepted, showing that the means (T-tests), medians (Wilcoxon tests) or distributions (Chi-Squared tests) are significantly different when applying two-sided tests and that one population's mean/median is significantly smaller/greater than the other in one-sided tests. P-values are reported to 3 decimal places or 2 significant figures to facilitate more focussed comparison and discussion of P-values between populations.

The abbreviations used in the section title represent the comparisons that have yielded significant differences; the changing variable being explored is emphasized in bold font. An overview of calculations that yielded significant outcomes is presented in Table 7, and an overview with all calculations performed and their respective P-values can be found in Appendix 6. These tables follow the abbreviations set out in Table 6 (reproduced below for convenience); the definitions are also included in the table captions.

The Shapiro-Wilk test was employed to test for normality of the Preliminary and BBC Datasets. Paired T-tests were used to analyse the similarity of sub-populations within the Preliminary Dataset. The Wilcoxon test (rank-sum and two-sided unless otherwise stated) was employed to analyse similarity of Individual data and the Chi-Squared test was used for Class data and binned Individual data.

*Table 6: Abbreviations used to analyse and discuss the BBC Dataset.*

| Individual data | Class data | Researcher classification | Participant classification | Natural terrain | Developed terrain | Mixed terrain | Before Error CC | After Error CC |
|---|---|---|---|---|---|---|---|---|
| **I** | **C** | **F** | **T** | **N** | **D** | **M** | **B** | **A** |

*Table 7: Table showing key comparisons that have resulted in statistically significant outcomes (with one exception included for illustrative purposes). The section column defines the area of analysis which corresponds with the section; the description column focusses in on the area within the section analysed; the variables column specifies the two sub-populations compared. The P-values are presented under their respective test names. Abbreviations: Individual (I), Class (C), Researcher's classification (F), Participants' classification (T), Natural (N), Developed (D), Mixed (M), Before Error CC (B), After Error CC (A).*

*Yellow fields indicate statistically significant P-values (a significant difference was found between the two variables being compared); green fields indicate relevant statistically insignificant P-values referred to in text; white numerical fields indicate insignificant P-value not referred to in text.*

*N/A: no calculation was performed where the test and comparison were not compatible.*

*(u): bin range included from 0.400 – 0.499 to 1.001 – 1.099; (l): bin range included from 0.400 – 0.499 to 0.950 – 1.000*

*a: Wilcoxon matched pairs signed-rank test on paired data, b: one-sided test using the alternative hypothesis that the first variable value is greater than the second variable value, c: one-sided test using the alternative hypothesis that the first variable value is less than the second variable value.*

| Section | Description | | P-value paired T-test | | |
|---|---|---|---|---|---|
| | | | Two-sided | One-sided | |
| 2.3.2. Preliminary Dataset | Researcher - Participants Before Error | | 0.039 | 0.020 | |
| | Researcher Right feet - Participants Right feet Before Error CC | | 0.036 | 0.018 | |
| | Researcher - Participants After Error CC | | 0.958 | 0.479 | |
| **Section** | **Description** | **Variables** | **P-value Wilcoxon** | | **P-value Chi-Squared** |
| | | | **Two-sided** | **One-sided** | |
| 2.3.3. AHI BBC Dataset | Sitting - Standing | N/A | 1.4e-10[a] | N/A | N/A |
| 2.3.4. Error CC | Before - After Error CC | **$IB_{(u)}$ - $IA_{(u)}$** | < 2.2e-16[a] | < 2.2e-16[ab] | N/A |
| 2.3.5. Individual - Class | Individual - Class | **$IB_{(l)}$ - CB** | N/A | N/A | 1.5e-03 |
| | | **$IA_{(l)}$ - CB** | N/A | N/A | 2.6e-06 |
| 2.3.6. Terrain per classification | Individual | **IFNB - IFDMB** | 6.5e-03 | 3.2e-03[c] | 0.158 |
| | | **IFNA - IFDMA** | 2.0e-03 | 1.0e-03[c] | 0.124 |
| | Class | **CFNB - CFDMB** | N/A | N/A | 0.029 |
| | Individual + Class | **FNB - FDMB** | N/A | N/A | 1.3e-03 |
| | | **FNA - FDMA** | N/A | N/A | 2.5e-05 |
| | | **TNA - TDA** | N/A | N/A | 0.048 |
| 2.3.7. Classification of Terrain | Researcher classification - Participants' classification | **IFDMA - ITDA** | 0.048 | N/A | 0.768 |
| 2.3.8. Agreed Terrain | Individual | **INB - IDMB** | 0.020 | 0.010[c] | 0.116 |
| | | **INA - IDMA** | 0.010 | 5.0e-03[c] | 0.113 |
| | Individual + Class | **NB - DMB** | N/A | N/A | 1.6e-03 |
| | | **NA - DMA** | N/A | N/A | 9.8e-05 |

### 2.3.1. Shapiro-Wilk test

The Shapiro-Wilk test was employed to determine whether the collected datasets are normally distributed, a prerequisite for determining which statistical tests can be employed to compare two populations. Seven Preliminary Dataset sub-populations and four BBC Dataset subpopulations were analysed. A full overview with all calculations performed and their respective P-values can be found in Appendix 6.

Three clear results were obtained:

1. All Preliminary Dataset sub-populations yielded P-values > 0.05. This means that the populations follow normal distributions. Parametric statistical tests were subsequently used to analyse this dataset.
2. The AHI values in both sitting and standing position (outliers > 1 removed) yielded P-values < 0.05. This means that the populations do not follow normal distributions. Non-parametric tests were subsequently used to analyse this data.
3. The collective Individual dataset yielded P-values < 0.05 both Before and After the Error CC. This means that the populations do not follow normal distributions. Non-parametric tests were subsequently used to analyse this dataset.

The Shapiro-Wilk test could not be applied to the categorical Class data from the BBC Dataset. However, the histogram (Figure 10) of this data does not appear to follow the shape associated with a normal distribution and thus non-parametric tests were used to analyse this dataset.

Based on these outcomes, parametric tests were chosen to analyse the Preliminary Dataset and non-parametric tests were chosen to analyse the BBC Dataset.

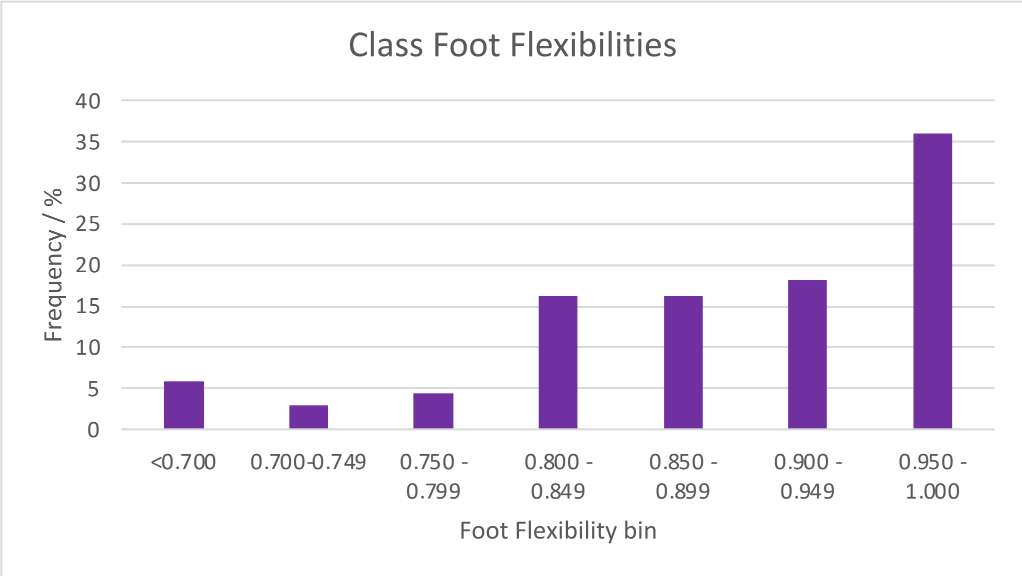


*Figure 10: Histogram of Class Foot Flexibilities showing the Frequency / % per Foot Flexibility bin.*

### 2.3.2. Preliminary Dataset

The FF values from feet measured by both the participants and researcher in the Preliminary Dataset were examined to see whether results from each measuring party yielded statistically significantly different means. This reflects the accuracy of measurement of the participants compared to the set of controlled measurements. The similarity in mean FFs between individual's left feet and right feet was also analysed.
A full overview with statistical calculations of all sub-population comparisons (n = 8) and their respective P-values can be found in Appendix 6.

Two sub-population comparisons yielded statistically significant differences:

1. Researcher – Participants (Paired T-test two-sided: P = 0.039, one sided: P = 0.020). When comparing FFs measured by the researcher and the participants, their means were found to be statistically different – although the measurements were taken from the exact same feet.
2. Researcher Right feet – Participants' Right feet (Paired T-test two-sided: P = 0.036, one-sided P = 0.018). The FFs from the right feet measured by both the researcher and the participants were found to have significantly different means.

The researcher's measurements of feet are found to be significantly different from the participants' measurements. The one-sided tests show that the FFs based on the researcher's measurements are significantly lower than those based on the participants' measurements (P = 0.020). With the addition of the Error CC, the comparative calculation between the researcher's and the participants' measurements returns a P-value of 0.958 for the two-sided test and a P-value of 0.479 for the one-sided test. Applying the Error CC (section 2.2.2) created more similarity between the outcomes of both measuring parties; the necessity to compensate for participants' systematic measurement error is confirmed. The Error CC was applied to measurements in the BBC dataset.

### 2.3.3. AHI BBC Dataset

The arch height index values of the BBC Dataset are separated into AHI-sitting and AHI-standing and compared (outliers >1 removed). This is solely done to illustrate that the arch height index is significantly different with an increase in weight-bearing (from 10% to 50% weight-bearing) hence justifying the use of the FF measure (AHI-standing/ AHI-sitting).

A statistically significant difference (P = 1.4e-10) is observed using the Wilcoxon signed-rank test. This means that the AHIs calculated in sitting and standing position have significantly different medians, thus justifying the use of the Foot Flexibility measure.

### 2.3.4. Error Correction Calibration: I**B**-I**A**

The effect of the Error Correction Calibration is analysed by comparing the Individual dataset Before the Error CC to the dataset After the Error CC. Although all values will decrease, it must be investigated if this shift affects the median significantly. One statistical comparison was performed, comparing all Individual FFs Before the Error CC to After the Error CC.

A statistically significant difference (Wilcoxon signed-rank both one- and two-sided: $P < 2.2e-16$) is observed when analysing I**B**-I**A**. This means that the median of the population changes significantly with the application of the Error CC. The one-sided test shows that Foot Flexibilities After the Error CC are significantly lower than Before the Error CC.
A Chi-Squared test is not performed on this dataset as this concerns paired data.

### 2.3.5. Individual – Class data: **I**B-**C**B, **I**A-**C**B

The similarity of distributions between the Individual dataset and the Class dataset was investigated to see if grouped versus individual data collection yielded unrelated distributions. Insight aids interpretation of results and comparisons between Individual and Class datasets.

Two statistical calculations were performed, comparing Individual FFs Before, and After the Error CC to Class data.

Both calculations showed statistically significant differences:

1. **I**B-**C**B (Chi-Squared: P = 0.002). The distribution of Individual FFs Before the Error CC was compared to the Class data.
2. **I**A-**C**B (Chi-Squared: P = 2.6e-06). The distribution of Individual FFs After the Error CC was compared to the Class data.

Chi-Squared tests showed that the distributions of **I**B-**C**B and **I**A-**C**B are significantly different, meaning that grouped and individual data collection either represent the population differently or that the Individual and Class data come from different populations. It can be observed that the P-value decreases when applying the Error CC to Individual data, suggesting that the dissimilarity between distributions can established with more certainty when applying the Error CC.

A Wilcoxon test was not performed as this dataset does not concern continuous data.

### 2.3.6. Terrain per classification: IF**N**B – IF**DM**B, IF**N**A-IF**DM**A, F**N**B-F**DM**B, F**N**A-F**DM**A, CF**N**B-CF**DM**B, T**N**A-T**D**A

The distributions of Foot Flexibilities between terrains were compared per classification method. These calculations directly relate to the research aim: exploring whether terrain is associated with higher or lower FF.
A full overview with statistical calculations of all sub-population comparisons (n = 16) and their respective P-values can be found in Appendix 6.

Six sub-population comparisons showed statistically significant differences:

1. IF**N**B-IF**DM**B (Wilcoxon two-sided: P = 6.5e-03, one-sided: P = 3.3e-03), between Natural and Developed + Mixed terrain, within the researcher's classification of Individual data Before the Error CC
2. IF**N**A-IF**DM**A (Wilcoxon two-sided: P = 2.0e-03, one-sided: P = 1.0e-03), between Natural and Developed + Mixed terrain, within the researcher's classification of Individual data After the Error CC.
3. F**N**B-F**DM**B (Chi-Squared: P = 1.3e-04), between Natural and Developed + Mixed terrain, within the researcher's classification of Individual + Class data Before the Error CC.
4. F**N**A-F**DM**A (Chi-Squared: P= 2.5e-05), between Natural and Developed + Mixed terrain, within the researcher's classification of Individual + Class data After the Error CC.
5. CF**N**B-CF**DM**B (Chi-Squared: P = 0.029), between Natural and Developed + Mixed terrain, within the researcher's classification of Class data Before the Error CC.
6. T**N**A-T**D**A (Chi-Squared: P = 0.048), between Natural and Developed terrain, within the participants' classification of Individual + Class data After the Error CC.

These results support the hypothesis that terrain influences FF. This trend is shown most clearly in the researcher's classification comparing Natural terrain to Developed + Mixed terrain, and is observed in Individual data, Class data as well as in Individual + Class data. The one-sided tests show that Natural terrain is associated with a lower median FF than Developed + Mixed terrain in the Individual dataset.

### 2.3.7. Classification of terrain: I**F**DMA-I**T**DA

The distribution of FFs per terrain as classified by the participants and by the researcher were compared to see if the method of classification made a difference. This allows insight into whether a systematic classification method enables consistency in the study.
A full overview with statistical calculations of all sub-population comparisons (n = 21) performed and their respective P-values can be found in Appendix 6.

One sub-population comparison showed a statistically significant difference:

1. I**F**DMA-I**T**DA (Wilcoxon: P = 0.048), comparing the researcher's classification Developed + Mixed with the participants' classification of Developed terrain within the subset of Individual data After the Error CC.

It is shown that the medians of I**F**DMA and I**T**DA are significantly different, suggesting that in only 1 out of 21 occasions the classification method has yielded distinctive FF medians for a certain terrain.
Chi-Squared tests have not yielded statistically significant differences between classification methods of the data, P-values for these calculations can be found in Appendix 6.

### 2.3.8. Agreed Terrain: I**N**B-I**DM**B, I**N**A-I**DM**A, **N**B-**DM**B, **N**A-**DM**A

Postcodes that were classified the same by both the researcher and participants were isolated and, of these, the FFs between terrains were compared to see if the consensus strengthened the statistical outcome.

A full overview with statistical calculations of all sub-population comparisons (n = 11) performed and their respective P-values can be found in Appendix 6.

Four sub-population comparisons showed statistically significant differences:

1. I**N**B-I**DM**B (Wilcoxon two-sided: P = 0.020, one-sided: P = 0.010), between Natural and Developed + Mixed terrain within the subset of Individual data Before the Error CC.
2. I**N**A-I**DM**A (Wilcoxon two-sided: P = 0.010, one-sided: P = 0.005), between Natural and Developed + Mixed terrain within the subset of Individual data After the Error CC.
3. **N**B-**DM**B (Chi-Squared: P = 0.002), between Natural and Developed + Mixed terrain within the subset of Individual + Class data Before the Error CC.
4. **N**A-**DM**A (Chi-Squared: P = 9.8e-05), between Natural and Developed + Mixed terrain within the subset of Individual + Class data After the Error CC.

Where both the researcher and the participants classified postcode the same, a clear trend can be observed that the distribution of Foot Flexibilities associated with Natural terrain is significantly different to those associated with Developed + Mixed terrain. This is observed in Individual data and Individual and Class combined data. The one-sided tests show that Natural terrain is associated with lower FFs than Developed + Mixed terrain in the Individual dataset.

### 2.3.9. Gender and Age

Foot Flexibilities were compared between genders and ages to see if these influence the arch flexibility.
A full overview with statistical calculations of all sub-population comparisons (n = 6) performed and their respective P-values can be found in Appendix 6.

No calculations yielded relevant statistical outcomes. This means that between the ages of nine and eleven, neither age nor gender has shown to influence Foot Flexibility (Appendix 3). Further discussion is beyond the scope of this research.

## 2.4. Discussion & Conclusion

From the results presented above, a trend is observed wherein Foot Flexibilities are found to significantly differ ($P < 0.05$) between those who grow up on Natural terrain and those growing up on Developed + Mixed terrain. This means that terrain indeed affects the structure of a developing foot. Moreover, Wilcoxon one-sided tests have shown that Natural FFs have a significantly lower median than Developed + Mixed FFs following the researcher's classification (sections 2.3.6 and 2.3.8). Up until now, absolute FF values have mostly been mostly ignored. However, to adequately draw a conclusion on the extent to which arch flexibility is associated with a certain terrain and view these results in the framework of the literature, the absolute values must be discussed.

Table 8 shows a summary of the FFs collected in the BBC Dataset, categorised per sub-population. The mean and median increase much more when going from Natural to Developed + Mixed for the researcher's classification than from Natural to Developed for the participants' classification (Table 9). For example, the mean and median increase approximately by 0.08 and 0.1 respectively for the researcher's classification, whereas following the participants' classification the mean only increases by 0.02 and the median FF value negatively changes going from Natural to Developed terrain. This negative change opposes the general trend observed. These observations suggest that the two terrains are separated more structurally by the researcher's classification. The greatest FF increase is found in agreed terrain (Table 9); it can be theorised that this classification is characterised by more homogenous- and obvious-appearing terrain, therefore having a more pronounced effect on the morphology of the feet. However, further research is needed to confirm this theory.

The Class data sub-populations (CFNB, CFDMB, CTNB, CTDB) all have the modal bin of 0.950 – 1.000 regardless of classification method (Appendix 3). This dataset does not allow for additional comparisons to be made beyond the Chi-Squared calculations performed.

*Table 8: The mean ±SD, median and n of FFs per Individual sub-population.*

| | Researcher's classification | | | | Participants' classification | | | |
|---|---|---|---|---|---|---|---|---|
| | Before Error CC | | After Error CC | | Before Error CC | | After Error CC | |
| | **IFNB** | **IFDMB** | **IFNA** | **IFDMA** | **ITNB** | **ITDB** | **ITNA** | **ITDA** |
| **Mean** | 0.839 ±0.151 | 0.919 ±0.118 | 0.804 ±0.147 | 0.892 ±0.121 | 0.847 ±0.157 | 0.868 ±0.140 | 0.816 ±0.155 | 0.837 ±0.139 |
| **Median** | 0.849 | 0.947 | 0.815 | 0.921 | 0.881 | 0.873 | 0.839 | 0.838 |
| **n** | 95 | 31 | 97 | 34 | 57 | 69 | 59 | 72 |
| | | | | | | | | |
| | Agreed terrain | | | | | | | |
| | Before Error CC | | After Error CC | | | | | |
| | **INB** | **IDMB** | **INA** | **IDMA** | | | | |
| **Mean** | 0.824 ±0.160 | 0.926 ±0.107 | 0.785 ±0.152 | 0.893 ±0.109 | | | | |
| **Median** | 0.844 | 0.967 | 0.804 | 0.925 | | | | |
| **n** | 42 | 16 | 42 | 17 | | | | |

*Table 9: The increase in FF when going from Natural to Developed (+ Mixed) terrain per sub-population.*

| | **IFNB - IFDMB** | **IFNA - IFDMA** | **ITNB - ITDB** | **ITNA- ITDA** | **INB - IDMB** | **INA - IDMA** |
|---|---|---|---|---|---|---|
| **Δ Mean** | 0.080 | 0.088 | 0.021 | 0.021 | 0.102 | 0.108 |
| **Δ Median** | 0.098 | 0.106 | -0.008 | -0.002 | 0.123 | 0.121 |

The classification method of terrain has been shown to be critical in assessing the effect of terrain on Foot Flexibilities (section 2.3.6.). Two methods of classifying terrains were employed in this study: one where each postcode classification is based on the interpretation of man-made and natural terrain made by another individual or a group of participants; one where all postcodes were interpreted with the use of Google Maps by one researcher, who also had the additional Mixed category to choose from. Both variable aspects (classifying party and added Mixed category) of the classification process are expected to influence the outcomes based on these methods. However, as the trend is only consistently observed for Natural versus Developed + Mixed terrain following the researcher's classification (Table 10 10), the consistency of the method is the more likely reason for the trend being observed more in the researcher's method. Still, the method followed by the researcher could be refined to determine terrain more consistently and specifically, as it is shown that the Mixed category is more consistent with Developed terrain as these, opposite the Natural category, yield a significant difference. The researcher's method can be concluded to have separated the postcodes in a structural manner. Following this classification, a statistical difference in Foot Flexibilities between participants living on Natural terrain and participants living on Developed + Mixed terrain can be observed consistently, as well as significantly lower FFs associated with Natural terrain than Developed + Mixed terrain ($P \leq$ 3.3e-03).

For the participants' classification, the only significant difference between Natural and Developed terrain was found in the Individual + Class category (T**N**A-T**D**A (Chi-Squared: P = 0.048)) (section 2.3.6). This would imply that with both datasets combined, the expected trend can be observed that marginally overcomes the randomness in their classification method to a statistically significant degree. Despite the lack of consistently observed significant results for the participants' classification (Table 10), the two classification methods result in different terrain-focused sub-populations only 1/27 times (section 2.3.7, Appendix 6). The fact that similar sub-populations arise from both methods of terrain allows for speculation that more randomised overlap is present in the participants' classification, which prevents significant differences to be found when analysing terrain based on their classification.

Acknowledging that no objectively true classification exists, postcodes allocated the same terrain by both methods were compiled in anticipation to form the most representative determination of terrain. The statistical outcomes of the agreed terrain category were not more significant than the researcher's classification on its own, but in fact fell between the researcher's and the participants' classification (e.g., Wilcoxon two-sided: IFNB-IFDMB P = 0.006, ITNB-ITDB P = 0.5, agreed terrain INB-IDMB P = 0.02) (section 2.3.8). The larger difference in mean and median going from Natural to Developed + Mixed terrain (Tables 8 and 9) is not reflected by a more discriminative P-value, which is likely due to the much smaller agreed terrain population. Ultimately the same trend can be observed for the agreed terrain category as previously found in the researcher's classification, but with a lesser degree of certainty. It has been found that the classification method impacts the consistency of the study, and a systematic approach yields clearer results.

Placing these results within an existing literature framework is problematic, as only a few studies could be found exploring the relationship between terrain and foot characteristics.

Where differences have been reported, these relate to the static foot types[51,52] as opposed to arch flexibility as investigated in the current study. Other differences between the literature and this study make further comparisons challenging, such as the lack of explanation of the terrain classification method[52] and the difference in shoe wearing habits[51], as participants of the current study are expected to commonly wear shoes. Although both publications found the urban areas to correlate with more flat feet, a direct relationship cannot yet be stated between flat feet and rigid arches in urban environments.

A statistically significant difference is observed between the Individual dataset and the Class dataset (P = 1.5e-03), which becomes more significant After the application of the Error CC (P = 2.6e-06) (section 2.3.5). The dissimilarities between these populations can be hypothesised to originate from a few core differences. The most obvious difference is that the Individual datapoints represent singular absolute FF values whereas Class datapoints represent the bin that was the most present within a group of participants. Without information about the size of the group and the proportion making up the modal frequency, all datapoints in the Class population are regarded to carry equal weight, which is unlikely to be representative of reality. Additionally, all mode-non-compliant feet are disregarded, upon which information about the distribution among the other bins within that group is lost. Nevertheless, the Class dataset includes results from 170 different schools, thus is likely to represent a thorough cross-section of the UK population. The Individual dataset consists of 153 datapoints but is only representative of 13 schools. While, according to the participants, this dataset is representative of both terrains approximately equally (45% Natural, 55% Developed), the researcher classified only one postcode as Developed terrain. This means that a statistical outcome could never be determined without the addition of Mixed to Developed terrain. Even with Developed + Mixed terrain, the categories were distributed unevenly according to the researcher's classification (75% Natural, 25% Developed + Mixed). Contrastingly, the Class terrains classified by the researcher were found to be more equally distributed with 49% Natural, 18% Developed and 33% Mixed, but unequally distributed following the participants' classification with 16% Natural and 84% Developed. As the distributions of terrain between the Individual and the Class datasets are so dissimilar, it could be hypothesised that the distributions of FFs are also dissimilar based on the premise that terrain influences FF.

Regardless of the difference in data structure via modal bins and individual values, the difference in number of schools and variety included, and the difference in terrain distributions between the two datasets, both datasets were considered appropriate to investigate the relationship between Foot Flexibility and terrain and have yielded significant outcomes (Table 7 and 10). Even combining the Individual and Class categories yielded trends confirming statistically significant outcomes.

However, not every dataset yields significant results as reliably; partially reflective of the classifying party (Table 10). The Class dataset seems to bear least reliable foundation to conclude on the relationship between terrain and Foot Flexibility, yielding only one statistically significant result from the three comparisons from which significant results could be expected (Table 10). The Individual and Individual + Class datasets yield four and five significant results out of six comparisons, respectively. This difference is expected to originate from the different classification methods. It seems unlikely that Individual + Class is a more reliable dataset than Individual alone, considering that the Class dataset lacks so much distributional data.

*Table 10: Number of statistically significant outcomes when comparing two terrain types (Natural and Developed (+ Mixed)), organised by classification and dataset (Individual, Class, and Individual + Class).*

| **Dataset** | **Classification** | | | |
|---|---|---|---|---|
| | Researcher's Natural – Developed + Mixed | Participants' Natural – Developed | Agreed terrain Natural – Developed + Mixed | Total |
| Individual | 2/2 | 0/2 | 2/2 | 4/6 |
| Class | 1/1 | 0/1 | 0/1 | 1/3 |
| Individual + Class | 2/2 | 1/2 | 2/2 | 5/6 |
| Total | 5/5 | 1/5 | 4/5 | |

A significant difference in median is observed comparing the collective Individual dataset Before and After Error CC (Wilcoxon signed-rank both one- and two-sided: $P < 2.2e-16$) (section 2.3.4). Equally, the Error CC has been shown to affect the P-value when comparing two terrains (Appendix 6). From the fifteen calculations where the effect of the Error CC can be observed, on thirteen occasions the P-value is found to decrease, of which one calculation becomes statistically significant After the application of the Error CC (TNA-TDA).

The other twelve decreasing P-values do not alter the significance status of the result; of these, six reduce remaining significant and six reduce still falling short of significance. The reducing of these first-mentioned six P-values suggests that the difference between the distributions of Foot Flexibilities separated by terrain become more certain when the systematic measurement error is accounted for. Conversely, in two instances the P-values become larger with the application of the Error CC (Chi-Squared: IT**N**A-IT**D**A $\Delta$P = 0.352 and F**NM**A-F**D**A $\Delta$P = 0.112) (Appendix 6), but still the significance status of the comparison remains unchanged.

As expected, generally similar significance status outcomes are found between terrains Before, and After the Error CC, as both sides of the calculation are shifted equally; the only substantial difference (between the two populations) being the inclusion of five previously considered outliers. When analysing the effect of the Error CC on the Individual values, the effect is most apparent in the increase in FFs in bracket 0.750 – 0.799 as shown in Figure 11. The Error CC was designed and implemented to compensate for the participants' systematic measurement error as established in the Preliminary Dataset (section 2.2.2). The Error CC will be more important when absolute Foot Flexibility values need to be discussed and to enable comparison with other studies discussing Foot Flexibility.

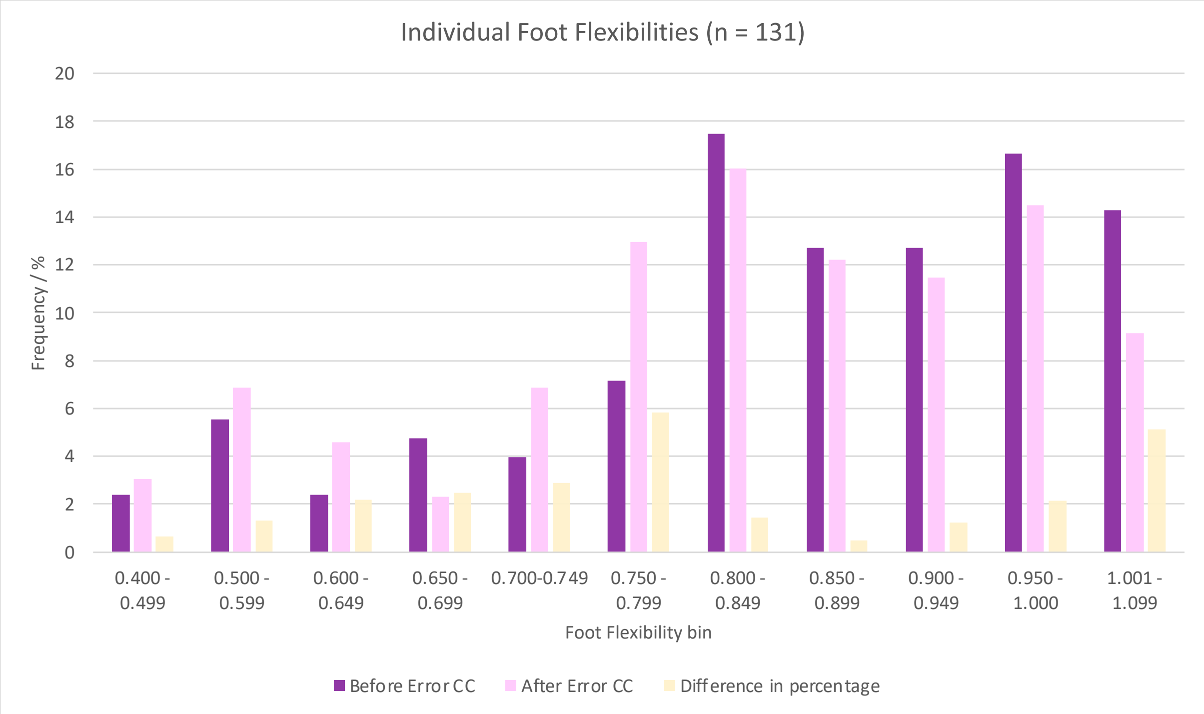


*Figure 11: The frequency / % of Individual Foot Flexibilities per bin Before the Error CC and After the Error CC, as well as the difference in percentage per bin as a result of the Error CC.*

When comparing the Preliminary and BBC Dataset, a few dissimilarities were noted. The most obvious dissimilarity was briefly discussed in section 2.2.4, where the FFs found through the BBC Dataset reached much lower values than those obtained through the Preliminary Dataset (lowest FF value 0.629). The lowest FFs reported in the BBC Dataset are undoubtedly inaccurate, but as 18% of all datapoints fell below the expected range (FF ≥ 0.700), this warranted a closer look. Upon removing all outliers according to the newly determined range: < 0.400 and ≥ 1.1, still 10% of datapoints (n = 13) fell below the lowest Preliminary value. It is unclear whether the low values are the result of measurement error, whether arches are more flexible in children than originally anticipated, or to which degree a combination of these two factors play a role.

Although the AHI was found to be the most reliable and valid method of assessing the arch height[27], it has been noted that inexperienced physical therapists have yielded comparatively lower inter-rater reliability[43]. This effect is expected to increase when participants between the ages of nine and eleven years old are obtaining the measurements. Moreover, it can be hypothesised that the young age of the participants can play a part in the reliability with which measurements can be obtained from them. The reliability of determining the AHI in children between the ages of six to twelve years old[8] has the lowest reported intratester ICC values (0.80 – 0.87) of those presented in Table 2 (section 1.1.3), although this is not a consistent observation, as an intra-tester ICC value of 0.99 has also been reported for participants between the ages of eight to twelve[15]. The ages in these publications are consistent with the ages used in the current study.

These two reliability observations seem plausible factors to influence the accuracy of the results. However, this probable inaccuracy was anticipated and mediated through the use of the Error CC. The Error CC assumes all results as equally inconsistent, which may not be a true representation of the measurement error; however, it was compensated for as well as the current circumstances allowed.

AHI values for participants of similar ages to the demographic of the current study are reported of 0.36[8] and 0.35[15] for sitting position and 0.33[8] and 0.32[15] for standing position. Calculating the FF using these reported averages would give FF values of 0.917[8] and 0.914[15]. The latter value has been more accurately reported as 0.92 for obese participants and 0.95 for non-obese participants.

In the current study, the average AHI-sitting values are 0.378 and 0.386 for the Preliminary Dataset and the BBC Dataset respectively, and the average AHI-standing values are 0.322 and 0.329 for the Preliminary Dataset and the BBC Dataset respectively.

The average FF values from the Preliminary Dataset and BBC Dataset Before and After Error CC are 0.855, 0.859 and 0.827 respectively. The relatively high AHI-sitting values (high arch) seem to give way to the low FF values (more arch deformation).

These discrepancies would make it seem that the values reported in the current study are skewed. However, the literature has reported population sizes of 20[15] and 30[8] and is performed on local participants, which could explain differences to some degree.

Comparative calculations showed both similarities and differences between the populations of the Preliminary and BBC Dataset depending on the test employed, sub-populations compared and application of the Error CC. However, as the Preliminary Dataset has a smaller population and consists of only three schools, the lack of similarity between the two populations can be disregarded. What the Preliminary Dataset has revealed, however, is that the Error CC compensates for the systematic measurement error observed in that population. As the aim of analysing this population was to determine discrepancies in method between the researcher and the participants and to refine the experimental design for subsequent research, comparability of FF outcomes is less relevant.

This research was conducted with participants between the ages of nine and eleven years old. This is around the age of peak MLA development[52] or arch maturation[40,53] (sources differ); the participants are expected to have lived on such terrain during the development of their arch. This enables investigation into the effect of terrain on the foot's structural morphology, without much interference from varying terrains. Although it is likely that some participants would have relocated, this is not expected to be the case for the majority of the demographic, especially having relocated to opposite types of terrain.
Foot Flexibility has not been found to differ between genders or ages in the current study (section 2.3.9), thus supporting the findings that the arch has fully developed before the age of 9. Race is another intrinsic factor that may influence arch structure. This is not taken into consideration and could influence this study's results. Racial diversity and distribution of participants throughout the UK may influence the Foot Flexibility commonly occurring per postcode, thereby impacting potential racial bias of this classification method. Some previous studies have commented on racial aspects in relation to foot characteristics, mostly relating to static measurements or ratios[53,54,64], not the deformation of the arch as investigated in the current study.

The participants were asked to include whether they had ever broken a bone in their foot or leg in the participant survey (Appendix 2). There seemed to be no association between the FF and prevalence of broken bones, as these were distributed across the FF bins (one broken bone in bin 0.500 – 0.599; one in 0.700 – 0.749; two in 0.750 – 0.799; two in 0.800 – 0.849; two in 0.850 – 0.899; three in 0.950 – 1.000).
Research relating foot characteristics to injury patterns report mostly on foot types based on static measurements, instead of the dynamic behaviour of a foot as in the current study. A lack of relationship was found between the arch flexibility and the foot type (planus, rectus,

cavus)[14,18]. Therefore, previously investigated injury patterns cannot be linked to amount of deformation of the arch under the application of weight.

In summary, the terrain that children live on has been statistically shown to influence their Foot Flexibility, i.e., the amount of deformation of the arch under bodyweight (sections 2.3.6 and 2.3.8). Applying the Error CC and following the researcher's classification of Individual data, participants living on a Natural terrain had an average FF of 0.804 with a median FF of 0.815, while participants living on Developed + Mixed terrain had an average FF of 0.892 with a median FF of 0.921 (Table 8). Data from the Natural terrain (Figure 12) is more evenly distributed around the mode, whereas the histogram representing Developed + Mixed terrain (Figure 13) looks more negatively skewed. These observations correspond with the average and median FF values falling in the modal bin for the Natural terrain (0.800 – 0.849), and the average and median FF values of Developed + Mixed terrain falling in the two bins below the modal bin (0.950 – 1.000). Statistical analyses showed Natural and Developed + Mixed populations to be significantly different and Natural Individual FFs to be significantly lower than Developed + Mixed Individual FFs ($P = 1.0e\text{-}03$) (Table 7). This means that lower FFs (i.e., more flexible arches), are associated with living on Natural terrain and stiffer arches are associated with living on Developed + Mixed terrain. Figure 11 appears to show a bimodal distribution with two distinct peaks: one at bin 0.800 – 0.849 representing the Natural terrain FFs and one at 0.950 – 1.000 representing the Developed + Mixed terrain FFs. These visual observations cannot be observed for the Class data (Figure 10), where the data is negatively skewed, illustrated by the modal bin at the highest end at 0.950 – 1.000.

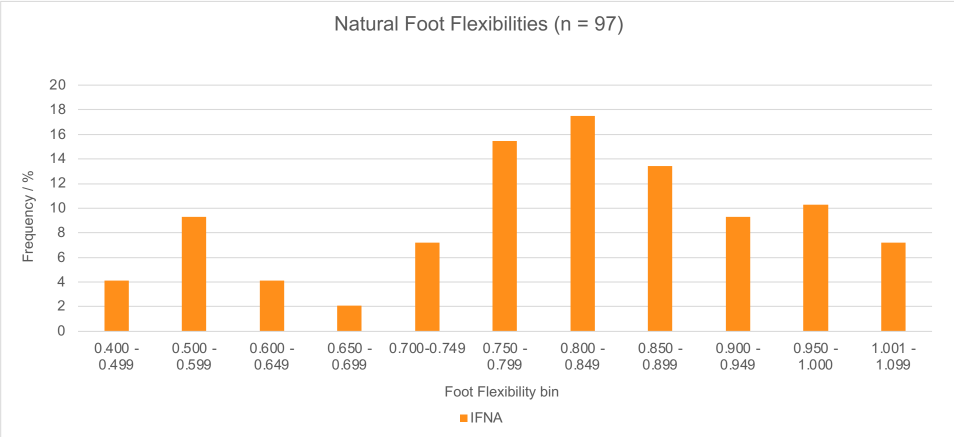


*Figure 12: Histogram showing the distribution of Foot Flexibilities for Individual datapoints classified as Natural terrain by the Researcher After the Error CC.*

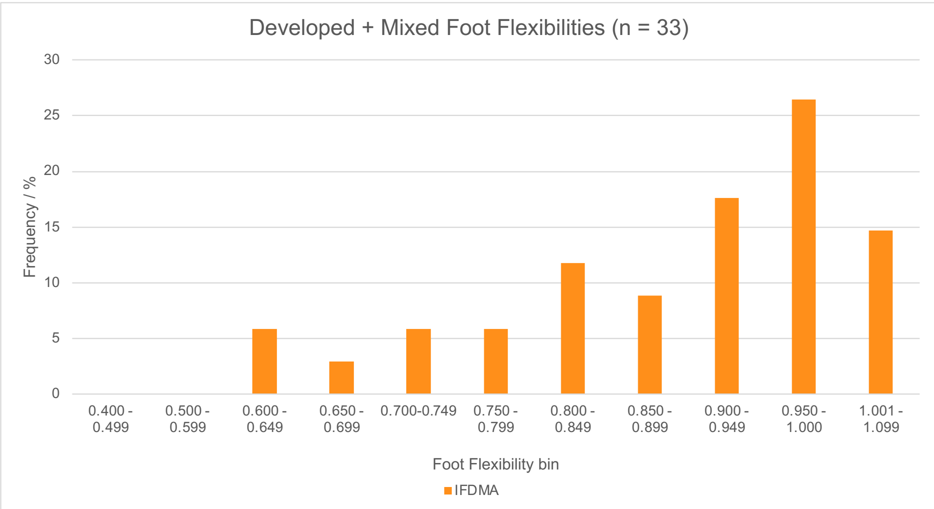


*Figure 13: Histogram showing the distribution of Foot Flexibilities for Individual datapoints classified as Developed + Mixed terrain by the Researcher After the Error CC.*

The data collected evidences that the terrain an individual grows up on directly affects the structural development of their foot. This can be concluded as for the researcher's classification, Foot Flexibilities originating from Natural terrain were found significantly distinctive from Developed + Mixed terrain FFs ($P \leq 0.029$). The conclusion is reinforced by the one-sided Wilcoxon tests showing Individual Natural FFs to be significantly lower than Developed + Mixed FFs ($P \leq 3.2e\text{-}03$). This observation has two implications:

1. terrain significantly influences the FF
2. a standardised classification protocol is required to investigate the implications of terrain consistently.

As this first outcome is observed consistently, the trend is shown not to be based on chance and additional weight can be attributed to the conclusion. The second implication is supported by the lack of consistent significant outcomes following the participants' classification.

These conclusions are specific to the demographic of the study (UK residential children aged 9 – 11 years old) and would require additional research to extrapolate for different populations. Assumptions about an individual's Foot Flexibility cannot be made based purely on their residential postcode.

It was considered that the participants may not necessarily spend most of their time outside of school on the terrain that is most apparent in their area. The participant survey included questions relating to the surface on which the participants spend their time outside of school (Appendix 2), but the analysis of this additional data falls beyond the scope of this study. Some discrepancy is expected to arise from this nuance.

## 2.5. Limitations: the influence of terrain on Foot Flexibility

Certain limitations are associated with the research presented. The main limitations are related to the data collection and the postcode classification. Although the method of data collection allowed for a large sample to be taken from varied locations, some disadvantages are associated with it. The data collected by the participants can be argued to be inherently unreliable, as the measurements were collected by participants between the ages of 9 – 11 years old. As it has been shown that inexperienced physical therapists yield lower reliability values[43], it can be expected that young participants would yield low reliability. Additionally, rulers were used to measure the foot dimensions, where it has been found that callipers or the AHIMS would increase accuracy[10,25]. Moreover, the participants were instructed by their schoolteachers, who had received written online instructions. These instructions could have been misinterpreted and consequently yielded inconsistent data collection. To combat the expected inaccuracies associated with the measuring, the Error Correction Calibration was calculated with the Preliminary Dataset and applied to the BBC Dataset. Although the Error CC was based on a relatively small population size, it still provided insight about the direction and degree of the measurement error by the demographic.

Furthermore, the data was collected and presented in two separate formats: Individual and Class data. The Individual data had more statistical weight, but these 153 datapoints originate from only 13 schools. Consequently, a more narrow and uneven distribution of different terrains is represented, which is also shown in the terrain proportions classified by the researcher (115:1:37, Natural:Developed:Mixed) (section 2.2.3). Class data, on the other hand, consisted of 203 datapoints representing 170 postcodes. Although this dataset contained a broader distribution, it was not evenly distributed as classified by the participants (33:170, Natural:Developed). Moreover, the statistical significance of this dataset is drastically reduced due to the omission of data beyond the class modal bin. Information about the distribution among the full bin range and the population size would have resulted in more substantial results.

It has been found and discussed (section 2.4) that the terrain classification method is vital in the observation of relationships and that a more standardised method allows for more consistent results. The method of classifying terrains based on a postcode using Google Maps is a subjective generalisation of a greater area, and may not accurately reflect the surface on which participants would have spent the most time. Although these were all classified by a single researcher, eliminating inter-tester variability, the method is sensitive to bias and inaccuracies. One bias encountered is that Google Maps uses different filters without apparent reason (Figure 14). It is possible that this has influenced the perception of certain areas, where brighter colours seem to represent Natural terrain more than dull colours. Future work has been suggested to standardise the classification method to yield more consistent classification and results, which would also allow for a more equal distribution of terrains to be included in a study.

Other limitations include the lack of additional information, such as the participants' race, abilities and whether they have developed typically or atypically. Other factors such as shoe-wear habits, amount and type of physical exercise could all influence the flexibility of the arch. Although this information was gathered alongside the data, these factors were not taken into consideration in the current study. Lastly, this study has used AHI and FF as measures to compare foot structure. The AHI only takes a specific range of weight-bearing into consideration (10% to 50%WB), however, during gait, the foot supports 100% of an individual's weight. This partial range may omit a part of mobility and morphology; although using a wider weight-bearing range was not chosen as previously discussed in section 2.2.1, it is possible that a different method of classifying feet could produce different results.

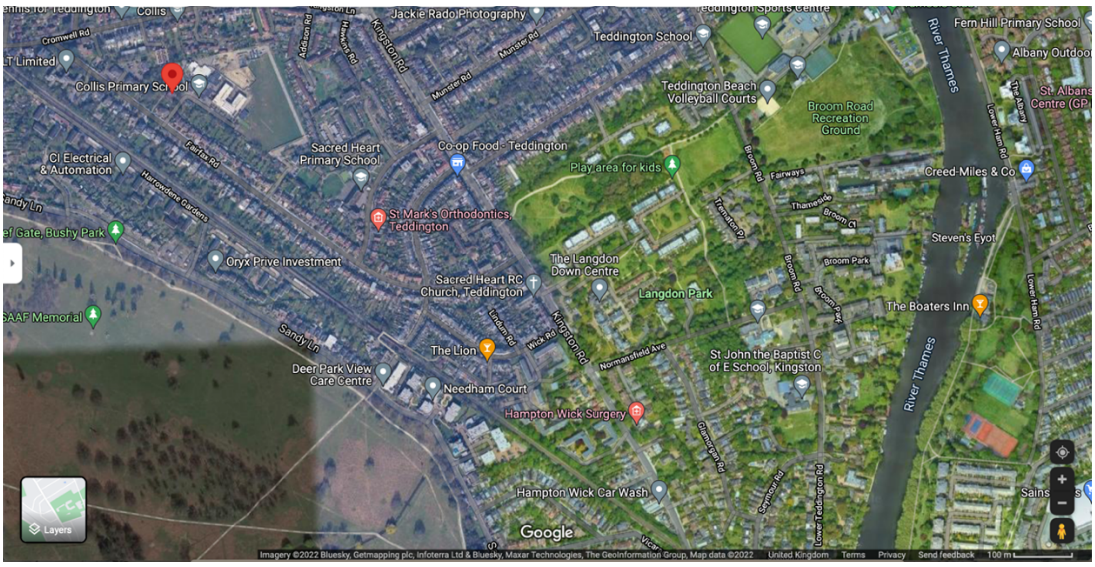


*Figure 14: A screenshot of Google Maps showing a single location portrayed in dull colours (left) and bright colours (right).*

## 2.6. Future work: the influence of terrain on Foot Flexibility

Future work regarding the effect of terrain on foot structure could solidify and expand on the outcomes obtained through this study. First, a more standardised classification method could be designed and subsequently applied to the current dataset. This would benefit future work performed in this field and facilitate comparison between studies. Additionally, conclusions of this study could be expanded by combining the Individual and Class datasets, to test whether the two data collection methods yield different populations or represent the same population differently. This could be done by randomly separating the Individual datapoints into "classes" and obtaining the modal bins from these, repeatedly. Then, these "classes" can be compared with the Class dataset to see if the populations are different using Chi-Squared tests. Furthermore, the additional data provided by the participants regarding the frequency and terrain type of their active hobbies could be considered and its possible effects investigated. However, as this is self-reported, this data is subject to recall bias. Additionally, significant differences have previously been reported between children's assessments and parents' assessments of physical activity[52]. One may not be more valid than the other, but the mixed estimation must be acknowledged or investigated further.

Any separate future studies could benefit from a single qualified clinician taking measurements and using an approximately even distribution of participants from the selected terrain types. Additionally, it would be interesting to see in which age brackets this relationship between Foot Flexibility and terrain can be observed. Furthermore, other classification methods can be applied to test whether these differentiate between participants growing up on different terrain types as well.

# 3. Dynamic movement of the arch

## 3.1. Introduction

Building on the understanding gained in the first chapter: the terrain an individual has grown up on influences the structural flexibility of their arch at the age of arch development, the second chapter explores various relationships within the dynamic expression of the static FF. Henceforth, the term 'youth terrain' will be used to indicate the terrain an individual has grown up on. The youth terrain-Foot Flexibility relationship is re-examined using adult participants, who have walked on varying terrain wearing smart insoles, thus enabling visualisation of the immediate dynamic response of foot morphology to terrain. Ultimately, a better understanding of the foot's biophysics is gained by investigating the relationships between FF and walking characteristics, and between arch deformation and the foot's function as a spring.

This research aims to increase understanding on four aspects of foot response: whether youth terrain has lasting influence on arch flexibility into adulthood; the relationship between foot structure and interaction with terrain; the dynamic response of the foot to terrain types; the relationship between Foot Flexibility and the foot's spring system.

It is expected that the association between youth terrain type and FF will persist into adulthood following the end of foot development, with diminishing effects with passing years. A difference in walking characteristics is expected between high and low FFs to accommodate for structural differences within the foot. Feet undergoing more arch deformation with weight are expected to exhibit a higher adaptability and therefore present more difference between walking characteristics on varying terrains. Generally, the foot is expected to adapt to the terrain to which it is exposed, potentially leading to different walking characteristics. Lastly, insight into the biophysics of the foot is expected to arise from this study, with the expectation that more deforming arches contain more energy.

The relationship between structural foot morphology, measured by FF, and the terrain an individual has grown up on, is hypothesised to be less clear for adults than for younger subjects. Additionally, walking characteristics are hypothesised to be influenced by both foot structure and terrain. Lastly, a more deforming arch is expected to have a spring constant of lower magnitude and spring energy of greater magnitude.

## 3.2. Methods

### 3.2.1. Data collection

Participant recruitment was through use of flyers (Appendix 7), which were distributed across the Canterbury campus of the University of Kent and placed on a weekly Postgraduate-bulletin email. Prior to participation, enquiring volunteers were sent the information sheet (Appendix 8) and were notified about the mobility requirements and shoesize restrictions, and were requested to wear trainers to the data collection session. Participants were included if their shoe size corresponded with the available smart insole (Figure 16) (NURVV Limited© 2009 Model: NR1) sizes: women's UK shoe sizes between 4.5 – 6, and 7.5 – 9.5 and men's UK shoe sizes between 5.5 – 6.5, and 8 – 10.

Seventeen healthy participants between the ages of 18 and 38 years old participated in the study. Upon each participant's arrival to the laboratory, they were asked to remove their shoes so the smart insoles could be fitted according to the manufacturer's specification underneath the already existing insole and of compatible size after they filled out the consent form (Appendix 9), General Health Questionnaire (Appendix 10), and the International Physical Activity Questionnaire (Appendix 11) for the three previous weeks. Each participant was given an alphanumerical participant number that was only linked to identifiable information on the consent form to allow for anonymisation of the data. An Additional Health Questionnaire (Appendix 12) was available in case participants would answer 'yes' to question 1 of the General Health Questionnaire "Has your doctor ever said that you have a heart condition or high blood pressure?"; the risk of participation could then be assessed and discussed with the participant. Next, Participants were given the Participant Data Sheet (Appendix 13) to fill out part 1, after which part 2 was filled out by the researcher. Each participant's height was measured with a stadiometer and their weight was collected using a body-scale. Then, participants were asked to sit on a chair with their knees bent at 90° and their legs resting with feet flat on A4 paper. Their foot length, truncated foot length and dorsum height were collected using a ruler. This was repeated with the participants in standing position, with their weight equally divided over both legs. The type of shoe was noted, and the thickness of the sole was measured.

For dynamic plantar data collection, each participant walked barefoot across the RS Foot Scan plate (Footscan® 2007 XL 2m plate). A mostly uninterrupted path was determined to enable the participants to maintain natural cadence while walking at self-selected velocity, to yield true gait measurements (Figure 15). Participants walked the path continuously until five satisfactory trials were collected where at least one foot on each lateral side made full contact with the plate.

The Footscan® 7.97 gait interface software was used to collect plantar data using the 'dynamic measurement' option. The participant's name (number), date of birth, weight and shoe size were collected in the software. The data was saved for each trial under the participant and trial numbers, and whether the measurement was obtained barefoot or shod (see below).

Following the barefoot data collection, the participants were prepared for shod data collection with fitted smart insoles. The correct fitting and working of the insoles were checked through the participants rolling from their heels to their toes and seeing if each sensor lit up in response to a pressure signal in the 'test your trackers' tab in the Nurvv Run app[65] (Figure 17). The plate data collection process was repeated while wearing shoes and insoles. Inside the app, the sex, height and weight of the participant were entered in the 'your details' tab. Then 'outdoor' option was selected under the 'Run', 'Quickstart' tab. The trial was then started while the participants walked the set path as described above to yield a 1-minute trial. Five 1-minute trials were collected to enable more data analysis, for example, the variability between trials per person and in case of data corruption.

Next, the participants went outside and walked on the pavement (Developed terrain) to collect five 1-minute insole readings to record walking parameters followed by a one 1-minute screen-capture of the 'test your trackers' tab. Finally, the participants walked through a woodland (Natural terrain) to collect the same data. The participants walked at a self-selected velocity, while the researcher followed along, starting new trials on the app every minute to collect the data without interrupting the participants' cadence. A log was kept of the participant number and the date and time of the Plate, Developed and Natural data collection. Upon return to the lab the insoles were removed and wiped.

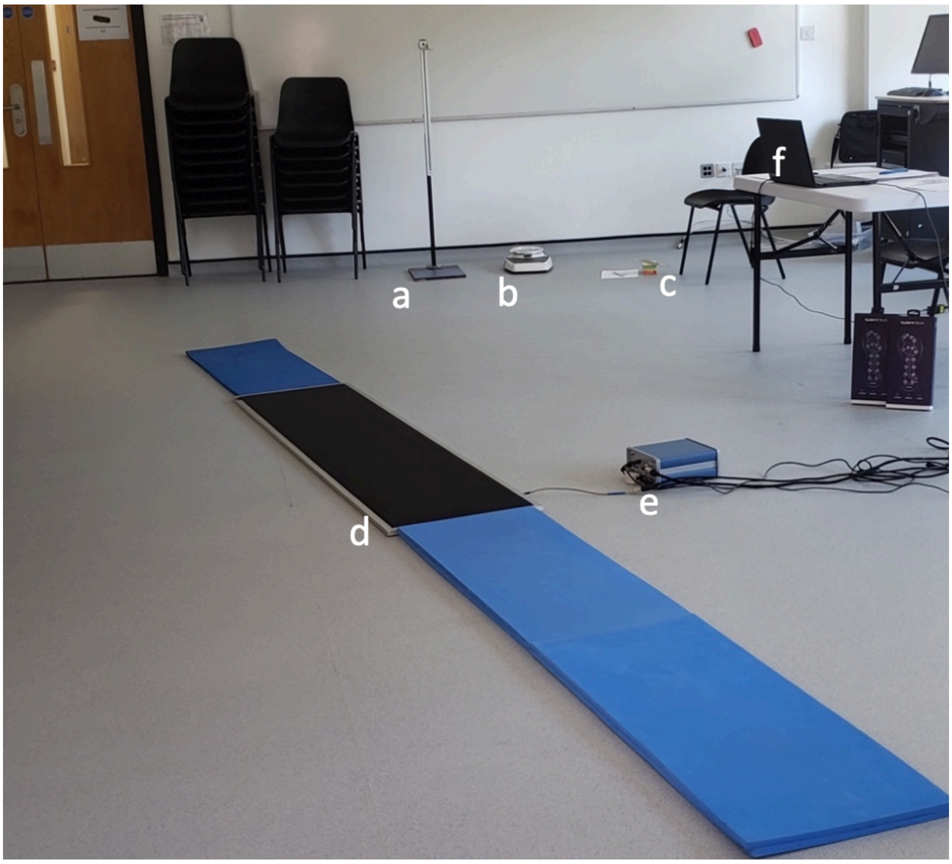


*Figure 15: The lab set up, with mats (blue) to even out the path connecting to the pressure plate, enabling an even surface surrounding the place of measurement. a: stadiometer, b: body-scale, c: foot measurement station, d: pressure plate, e: signal processing box, f: laptop connected to signal processing box.*


*Figure 16: Photo of insoles (back and front) and packaging. The 16 sensors are clearly visible on the back of the insole.*

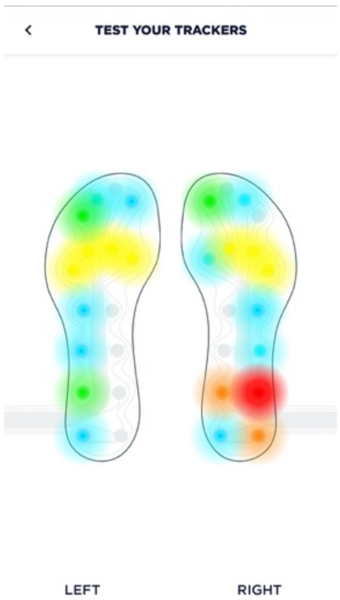


*Figure 17: Pressure map in the 'test your trackers' tab in the Nurvv Run app. In order of increasing pressure: blue, green, yellow, orange, red.*

### 3.2.2. Data extraction

*Pressure Plate Footscan data*

Walking trials collected using the RS Foot Scan had to be calibrated before they could be exported. This was done within the Footscan® 7.97 gait interface software per participant as follows:

Three trials with the best plantar pressure maps were chosen, one for each foot. Criteria included the whole foot being mapped and the clearest plantar pressure map. Rejected foot maps within the trial were deleted.

The length and the width of the foot were selected, aiming for the lines to be perpendicular (Figure 18). The length was outlined from the most posterior part of the heel to the most anterior part between the second and third toe[66]. The width was measured at the widest part along the metatarsal heads.

The 'last' of the foot was calibrated to accurately encompass the shape, size and direction of the foot (Figure 19). The pink outline (Figure 19) was altered to fit the pressure map correctly (Figure 19), where occasionally the software's assignment of the 'last' was unsuitable (Figure 19). Then, the vertical pink lines were set between the metatarsal heads and the white vertical lines were also set to isolate the metatarsal heads. This allowed the correct assignment of the foot zones: hallux, toes 2 – 5, separate metatarsal heads 1 through 5, midfoot, heel medial and heel lateral. The 'heel zone' and 'toe zone' separated the lateral from medial side of the heel and the hallux from the remaining toes respectively. Where necessary, singular pixels were isolated and assigned their zone.

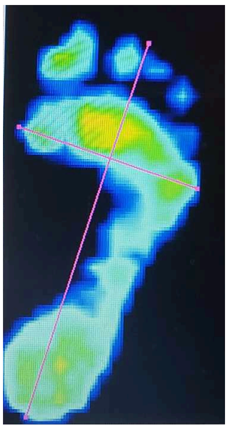

*Figure 18: Image showing a clear plantar pressure map including length and width definition lines.*

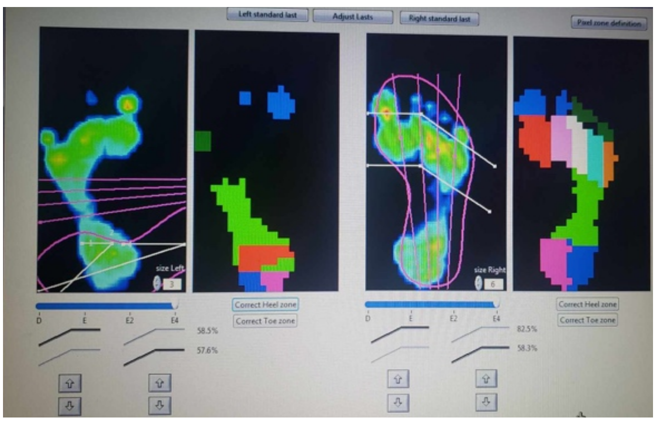


*Figure 19: Screen capture of Footscan® 7.97 gait interface software when calibrating the pressure maps. a: last is calibrated to reflect the pressure map of the foot accurately, b: software's own assignment of last.*

After calibration, the following parameters were exported for all three trials per participant: dynamic centre of force line, zone division, pressure/ force graphs, contact percentages, foot dimensions, dynamic report, and temporal and spatial parameters. As only barefoot data was anticipated to be used in this study, this process was limited to barefoot trials only. Ultimately, the data collected using the Footscan® 7.97 software was not used for analysis as additional calibration was needed due to an exportation issue.

### *Insole data*

Insole data was collected through five 1-minute measurements on both Developed and Natural terrain and five approximately 10 – 15 second measurements on the Plate on the Nurvv Run app. As these data could not be exported, they were copied into Excel for each terrain (Table 11). As the Plate data collection trials were short, some variables were only exported for Developed and Natural terrain (Table 11). At times, the app malfunctioned, and some data was missing. For 59 trials Pronation and Footstrike data was missing, and for 8 trials most data was missing. No data from the 8 missing trials could be recovered. For 34/59 trials, the complete dataset could be recovered with the help of Nurvv support. For 3/59 trials only the individual foot specific Footstrike data could not be recovered, for 2/59 trials only the individual foot Pronation data could not be recovered, and for 1/59 trials Pronation and Footstrike data relating to the right side could not be recovered. For 2/59 trials all Footstrike data could not be recovered and for 17/59 trials neither Pronation nor Footstrike data could be recovered (see Table 11 for the total number of successful trials). Once the data was exported and as much as possible recovered, the data could be analysed.

*Table 11: Overview of walking characteristics collected with the smart insoles. *The noted mean values and standard deviations (SD) are based on the mean value of successful trials per participant. The total number of successful trials per terrain (Plate, Developed, Natural) is included to illustrate where trials may be missing.*

| | Variables | Pace (min/km) | Power (W) | Running Economy (m/kcal) | Cadence (spm) | Step Length (m) | Pronation Neutral (%) | Pronation Left Over (%) | Pronation Left Under (%) | Pronation Left Neutral (%) | Pronation Right Over (%) | Pronation Right Under (%) | Pronation Right Neutral (%) | Footstrike Rear total (%) | Footstrike Left Rear (%) | Footstrike Left Mid (%) | Footstrike Left Fore (%) | Footstrike Right Rear (%) | Footstrike Right Mid (%) | Footstrike Right Fore (%) | Velocity (m/s) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Terrain | Abbreviations | **P** | **W** | **E** | **C** | **S** | **PN** | **PLO** | **PLU** | **PLN** | **PRO** | **PRU** | **PRN** | **FT** | **FLR** | **FLM** | **FLF** | **FRR** | **FRM** | **FRF** | **MS** |
| Plate | Mean* | 16 | N/A | N/A | 114 | 0.51 | 61 | N/A | N/A | N/A | N/A | N/A | N/A | 88 | 88 | 10 | 2.0 | 87 | 10 | 3.0 | 0.97 |
| | SD* | 2.6 | N/A | N/A | 5.9 | 0.058 | 30 | N/A | N/A | N/A | N/A | N/A | N/A | 3.8 | 4.2 | 3.8 | 3.5 | 3.7 | 3.3 | 2.3 | 0.13 |
| | Total number of runs | 87 | N/A | N/A | 87 | 87 | 87 | N/A | N/A | N/A | N/A | N/A | N/A | 87 | 82 | 82 | 82 | 82 | 82 | 82 | 87 |
| Developed | Mean* | 12 | 183 | 8.4 | 117 | 0.67 | 54 | 37 | 4.0 | 59 | 43 | 7.5 | 49 | 98 | 98 | 1.7 | 0.53 | 98 | 1.9 | 0.34 | 1.3 |
| | SD* | 1.0 | 36 | 2.8 | 5.7 | 0.042 | 35 | 42 | 8.9 | 40 | 42 | 19 | 38 | 0.36 | 0.45 | 0.37 | 0.61 | 0.46 | 0.47 | 0.41 | 0.11 |
| | Total number of runs | 88 | 86 | 86 | 86 | 86 | 88 | 75 | 75 | 75 | 75 | 75 | 75 | 87 | 77 | 77 | 77 | 76 | 76 | 76 | 86 |
| Natural | Mean* | 13 | 167 | 8.7 | 111 | 0.63 | 52 | 43 | 1.3 | 56 | 47 | 5.1 | 48 | 96 | 96 | 2.8 | 1.0 | 96 | 3.0 | 0.88 | 1.2 |
| | SD* | 1.4 | 35 | 2.7 | 5.7 | 0.051 | 31 | 36 | 1.9 | 35 | 36 | 13 | 32 | 2.1 | 1.5 | 1.1 | 0.90 | 2.9 | 1.9 | 1.1 | 0.13 |
| | Total number of runs | 86 | 80 | 80 | 80 | 80 | 86 | 71 | 71 | 71 | 71 | 71 | 71 | 86 | 72 | 72 | 72 | 72 | 72 | 72 | 80 |

### 3.2.3. Data analysis

*Static measurements*

Static measurements collected via the Participant Data Sheet were used to calculate the arch height index and Foot Flexibility (section 2.1.2, Equation 1 and Equation 2, respectively) for each participant. The postcodes were assigned terrains as previously (section 2.2.3.). The FFs were grouped per lateral side, terrain, and classification. Both lateral sides were tested for normality using the Shapiro-Wilk test, and one-way ANOVAs and a paired T-test were used for statistical analyses between sub-populations (section 3.3.1).

Following the findings that the arch functions as a spring[67], relationships between movement of the arch, Foot Flexibility, the spring constant ($k$) and spring energy ($E$) are explored following Hooke's law (section 3.3.4). Arch displacement ($x$) (horizontal length and vertical arch drop) and weight data collected via the Participant Data Sheet were used to calculate the net change in force (F) from sitting to standing (Equation 4), after which the spring constant (Equation 5) and spring energy (Equation 6) were calculated in horizontal and vertical directions (Appendix 14).

$$\Delta F = \frac{0.4m\,a}{2}$$

*Equation 4: Change in force experienced by the arch when changing from sitting to standing position, divided by two to account for bilateral standing.*

$$F = -k\,x$$

*Equation 5: Spring constant as a function of force and arch displacement according to Hooke's law.*

$$E = 0.5k\,x^2$$

*Equation 6: Spring energy as a function of the spring constant and arch displacement.*

Correlations between variables were calculated and graphs produced, visualising various relationships. Where the value for $x$ was 0, a value for $k$ could not be calculated and datapoints associated with these were thus omitted from the correlation calculations.

*Insole data*

Mean values per participant were calculated for each walking characteristic collected using the smart insoles before analysis. Deviations from the expected values were accepted as part of the collection process and their influence minimised by analysing averaged values.

The data was tested for normality using the Shapiro-Wilk test, and statistical tests were chosen accordingly (section 3.2.4). For section 3.3.2, the participants with the five highest and five lowest FFs per lateral side were selected; the insole data associated with these participants was used for analysis comparing interaction with terrain between foot structures. As there are no published guidelines on what determines a high or low Foot Flexibility, this approach was utilized to compare between the relatively high and low FF of this sample. Unpaired statistical tests were used to investigate whether the five highest and five lowest FFs yielded different outcomes, per terrain per characteristic.
Additionally, changes in response value for the walking characteristics between two terrains were calculated for both the high FF feet and low FF feet. The two ∆response values illustrate the difference in immediate adaptation to terrain between flexible and stiff arches. Then, correlations between all FFs per lateral side and the characteristics were calculated (section 3.3.2). Paired statistical tests were employed to investigate the similarity between responses to different terrain; these, and the post-hoc test results can be found in section 3.3.3. To further investigate the relationships among walking characteristics and between walking characteristics and terrain, correlations were calculated (section 3.3.3).

### 3.2.4. Data processing and statistical analysis tools

Excel was used to calculate the AHI and Foot Flexibility, to calculate means and look for outliers in the Insole data, and for biophysical calculations. The Shapiro-Wilk test was employed in POSIT Cloud[59] to determine if datasets and variables were normally distributed. Statistical analyses following the Shapiro-Wilk test were chosen according to guidelines[60] and performed in POSIT Cloud. For analyses concerning the static measurements, a paired T-test was employed to compare the mean FFs between left and right feet, and one-way analysis of variance (ANOVA) tests were employed to compare the mean FFs between terrains and classifications (section 3.3.1). Additionally, one- and two-sided tests were used to compare the means (unpaired T-test) and medians (Wilcoxon rank-sum) of walking characteristics between high and low FFs. Moreover, excel was used to calculate and visualise immediate adaptation to terrain for flexible and stiff arches. Finally, Posit Cloud was used to calculate Pearson and Spearman correlation coefficients, exploring any relationship between Foot Flexibility and interaction with terrain (section 3.3.2). Furthermore, a paired T-test, repeated measures ANOVA tests and Friedman ANOVA tests were used to analyse the effect of terrain on the foot's dynamic response. Post-hoc tests were chosen in deviation from the previously mentioned guidelines[60], instead, pairwise comparisons (paired T-test and Wilcoxon signed-rank) with the Bonferroni correction were used for consistency in accordance with other guidelines[68] (section 3.3.3). Finally, discussing associations between two variables, the Pearson and Spearman correlation coefficients were calculated, for the adhering to guidelines[60,69]. The test used for each calculation can be found in the table captions (section 3.3.4).

Correlation coefficients were calculated to elucidate linear relationships between two variables[69]. Guidelines for strength of association interpretation were simplified to include: strong association ($\pm$ 0.70 – 1); moderately strong association ($\pm$ 0.50 – 0.70); weak association (<$\pm$ 0.50).

An indication of the correlation coefficient's significance is included in the tables.

The alpha value of 0.05 is used to indicate statistical significance for all statistical tests.

### 3.2.5. Data interpretation

Various forms of data were collected from the seventeen participants of this chapter. Similar abbreviations are used to discuss the data as was used in the previous chapter (Table 12). Data collected from participants walking on the pressure plate in the lab is referred to as 'Plate data'; data collected from participants walking on the pavement is referred to as 'Developed data'; and data collected from participants walking in woodland is referred to as 'Natural data'.

*Table 12: Abbreviations used to discuss the analyses of the static measurements*

| Researcher classification | Participant classification | Plate | Natural Terrain | Developed Terrain | Mixed Terrain | Left foot | Right foot |
|---|---|---|---|---|---|---|---|
| **F** | **T** | **P** | **N** | **D** | **M** | **L** | **R** |

The smart insoles were used to collect data on 7 walking metrics (section 3.2.2); these and their definitions are described below[70]:

- Power (W): “rate of energy being expressed at a given moment”
- Running economy (metres/kcal): “the amount of energy that your body uses to run a certain distance”
- Pace (minute/km): “the amount of time taken to cover a given distance”
- Cadence (steps per minute (spm)): “measure of the rate at which a runner is taking steps”
- Step length (m): “the distance covered from the point of ground contact of one foot to the point of ground contact of the other foot”
- Pronation (%): “different ranges of motion are separated into Neutral Pronation, Under Pronation, and Over Pronation” (Figure 1, section 1.1.1)
- Footstrike (%): “Footstrike describes which part of a runner's foot – Rearfoot, Midfoot or Forefoot – makes initial contact with the ground”.

Pace is measured by the insoles averaged over the entire run, including directional changes and stops made by participants, for example at the start and finish of data collection, as well as during the run. Velocity was calculated using collected metrics, Cadence and Step length, and is stated in $ms^{-1}$. This is included as it is found to be a more representative measure of the gait cycle as it does not include directional changes or stops made by the participants. Both were included in statistical analysis for completeness; however, velocity was found to be a better suited measure to compare with other data in similar SI-units and thus is more frequently used in discussion. Pronation and Footstrike can be stated as an average of both feet, or specified per lateral side. “Footstrike total” refers to the average percentage of which initial ground contact was made with the rearfoot. Running economy is assumed to be measured by the Nurvv insoles using the participant’s height and weight, cadence, ground contact time and averaged energy consumption statistics, however, the exact details of this calculation are proprietary to the Nurvv company and are not available to the public.
Data and results are presented in tables and graphs, making use of the aforementioned abbreviations (Table 12). Data collected by the insoles are separated by terrain and are referred to as ‘Plate data’, ‘Natural data’, and ‘Developed data’, depending on if the participant was walking on the Plate, Natural terrain or Developed terrain, respectively.

## 3.3. Results

Seventeen healthy adult participants provided data for the analysis of the dynamic response of foot morphology to terrain. The population consisted of eight women and nine men between the ages of 18 and 38 years; Table 13 provides a demographic overview and anthropometric values collected.

*Table 13: A demographic overview of the population's (n = 17) and anthropometric values collected.*

| **Variable** | **Average (± standard deviation)** |
|---|---|
| Sex ratio (F/M) | 8 / 9 |
| Age (years) | 29 (± 6.8) |
| Height (cm) | 172 (± 8.2) |
| Weight (kg) | 79 (± 16) |
| Right AHI-sitting | 0.405 (± 0.031) |
| Left AHI-sitting | 0.399 (± 0.025) |
| Right AHI-standing | 0.373 (± 0.029) |
| Left AHI-standing | 0.360 (± 0.029) |
| Right FF | 0.923 (± 0.052) |
| Left FF | 0.904 (± 0.052) |

### 3.3.1. Youth terrain and adult FF

The effect of the youth terrain on Foot Flexibility as an adult is investigated.

The Shapiro-Wilk test was employed to determine whether the Foot Flexibilities were normally distributed to choose statistical tests accordingly to compare variables of interest, returning P-values of 0.145 (right feet) and 0.218 (left feet). These P-values > 0.05, the data was considered normally distributed, hence parametric tests were applied.

No significant differences were found in Foot Flexibilities between left and right feet, nor between terrains or classifications (Table 14). This suggests that Foot Flexibility is no longer associated with the terrain an individual has grown up on upon reaching adulthood. This could be due to participants having experienced different terrains throughout the years by relocating and their feet adapting. As with the BBC Dataset, the feet were analysed per lateral side to avoid potentially skewed outcomes[61]. These outcomes evidence the foot's ability to adapt after the structural development period.

*Table 14: Table containing P-values > 0.05 for variables tested. The category column indicates the area of analysis; the description column provides more detail; the variables column specifies the sub-populations compared. The P-values are presented under their respective test names.*
*Abbreviations: Left feet (L), Right feet (R), Researcher's classification (F), Participants' classification (P), Natural (N), Developed (D), Mixed (M).*

| **Category** | **Description** | **Variables** | **P-value<br>paired T-test** |
|---|---|---|---|
| Lateral side | Left - Right | **L - R** | 0.266 |
| | | | |
| **Category** | **Description** | **Variables** | **P-value<br>one-way ANOVA** |
| Terrain within classification | Left feet, participants' classification | **LTN - LTD - LTM** | 0.3 |
| | Right feet, participants' classification | **RTN - RTD - RTM** | 0.622 |
| | Left feet, researcher's classification | **LFN - LFD - LFM** | 0.91 |
| | Right feet, researcher's classification | **RFN - RFD - RFM** | 0.31 |
| Terrain and classification | Left feet: Natural - Developed + Mixed | **LFN - LTN - LFDM - LTDM** | 0.954 |
| | Left feet: Natural + Mixed - Developed | **LFNM - FTNM - LFD - LTD** | 0.468 |
| | Right feet: Natural - Developed + Mixed | **RFN - RTN - RFDM - RTDM** | 0.355 |
| | Right feet: Natural + Mixed - Developed | **RFNM - RTNM - RFD - RTD** | 0.783 |

### 3.3.2. The relationship between foot structure and interaction with terrain

The relationship between foot structure and interaction with terrain was explored by looking at the effect of FF on walking characteristics. Differences in dynamic response and immediate adaptability between flexible and rigid arches were investigated by comparing walking characteristics associated with the five highest FF feet and the five lowest FF feet. Additionally, the correlation between the full range of FF and walking characteristics was calculated.

In the vast majority of the calculations performed, low and high FFs did not show different interaction with terrain for walking characteristics (Table 15). Six statistically significant different outcomes were found between rigid and flexible arches (excluding comparing low and high FF for both lateral sides), of which five were observed amongst Plate data (Table 15). More flexible feet (low FF) were found to have a lower Pace (P = 0.013) and Neutral Pronation percentage (Plate: P = 0.036, Natural: P = 0.048), and a greater Step length (P = 0.045) and Velocity (P = 0.036). No significant difference was observed for both lateral sides for any variable. As only 6 out of 67 walking characteristics comparisons yielded significant results, these can potentially be attributed to chance, or the low population size used in these calculations (n = 5). These results suggest that the level of arch flexibility does not influence the interaction with terrain.

*Table 15: An overview of 69 comparative calculations comparing the medians and means of walking characteristics between groups with low Foot Flexibility (n = 5) and high Foot Flexibility (n = 5).*
*Yellow fields indicate statistically significant P-value, meaning that a significant difference was found between low and high FF.*
*[a]: one-sided test using the alternative hypothesis that the median associated with the low FFs is significantly less than the median associated with the high FFs. Results relate to data originating from the left feet. [b]: one-sided test using the alternative hypothesis that the median associated with the low FFs is significantly greater than the median associated with the high FFs. Results relate to data originating from the right feet.*
*All of FF, Pace, Power, Running Economy, Cadence, Step length and Velocity followed normal distributions and thus were compared using unpaired T-tests. Plate trials of Neutral Pronation, Footstrike total; and Plate and Developed terrain Footstrike rear (both lateral sides) were also analysed using unpaired T-tests.*
*Lateral side (left/right) Pronation values did not follow normal distributions and were therefore analysed using Wilcoxon rank-sum tests. Developed terrain Neutral Pronation and Footstrike total, as well as Natural terrain Neutral Pronation, Footstrike total, Footstrike rear (both lateral sides) were also analysed using Wilcoxon rank-sum tests.*

| Description | Terrain | P-value comparing low FF right feet with high FF right feet | P-value comparing low FF left feet with high FF left feet | P-value for one-sided test comparing low FF feet with high FF feet |
|---|---|---|---|---|
| **FF** | N/A | 0.003 | 6.3e-04 | N/A |
| **Pace** | Plate | 0.114 | 0.027 | 0.013[a] |
| | Developed | 0.216 | 0.107 | N/A |
| | Natural | 0.336 | 0.214 | N/A |
| **Power** | Developed | 0.730 | 0.880 | N/A |
| | Natural | 0.796 | 0.26 | N/A |
| **Running economy** | Developed | 0.624 | 0.202 | N/A |
| | Natural | 0.734 | 0.149 | N/A |
| **Cadence** | Plate | 0.216 | 0.178 | N/A |
| | Developed | 0.956 | 0.267 | N/A |
| | Natural | 0.963 | 0.416 | N/A |
| **Step Length** | Plate | 0.089 | 0.273 | 0.045[b] |
| | Developed | 0.168 | 0.170 | N/A |
| | Natural | 0.250 | 0.102 | N/A |
| **Neutral Pronation** | Plate | 0.976 | 0.072 | 0.036[a] |
| | Developed | 0.841 | 0.310 | N/A |
| | Natural | 0.841 | 0.095 | 0.048[a] |
| **Pronation Left over** | Developed | N/A | 0.222 | N/A |
| | Natural | N/A | 0.222 | N/A |
| **Pronation Left Under** | Developed | N/A | 0.656 | N/A |
| | Natural | N/A | 0.672 | N/A |
| **Pronation Left Netural** | Developed | N/A | 0.421 | N/A |
| | Natural | N/A | 0.209 | N/A |
| **Pronation Right Over** | Developed | 0.346 | N/A | N/A |
| | Natural | 0.841 | N/A | N/A |
| **Pronation Right Under** | Developed | 0.824 | N/A | N/A |
| | Natural | 0.833 | N/A | N/A |
| **Pronation Right Neutral** | Developed | 0.310 | N/A | N/A |
| | Natural | 0.841 | N/A | N/A |
| **Footstrike Total** | Plate | 0.432 | 0.700 | N/A |
| | Developed | 0.834 | 0.156 | N/A |
| | Natural | 0.691 | 0.753 | N/A |
| **Footstrike Left Rear** | Plate | N/A | 0.625 | N/A |
| | Developed | N/A | 0.790 | N/A |
| | Natural | N/A | 0.691 | N/A |
| **Footstrike Right Rear** | Plate | 0.628 | N/A | N/A |
| | Developed | 0.662 | N/A | N/A |
| | Natural | 0.753 | N/A | N/A |
| **Velocity** | Plate | 0.073 | 0.126 | 0.036[b] |
| | Developed | 0.532 | 0.146 | N/A |
| | Natural | 0.437 | 0.134 | N/A |

As high or low FF was not shown to have a statistically significant effect on the interaction with terrain, correlation coefficients were calculated to investigate if a linear relationship could be established. From the 148 calculations exploring correlations between FF and all walking characteristics, only three yielded significant results. A weak association was found between the left foot's FF and Pace on Natural terrain ($r = 0.49$, $P = 0.047$), a moderately strong association was found between the left foot's FF and Step length on Natural terrain ($r = -0.56$, $P = 0.021$), and a moderately strong association was found between the left foot's FF and Velocity on Natural terrain ($r = -0.52$, $P = 0.032$). A full overview of correlation calculations performed, and their respective P-values can be found in Appendix 15. All in all, Foot Flexibility does not appear to be correlated with walking characteristics.

Furthermore, it was investigated whether high or low FF influences the adaptability of feet between varying terrain. For each walking characteristic, all individual trial values for all terrain types collectively were combined per participant and the standard deviations for these were calculated (Table 16). For these calculations, individual trial values were used as opposed to the participant averages used in other sections, to allow analysis of the variability between responses. It was found that the standard deviation did not significantly differ between high and low FF feet, comparing their dynamic responses to the varying terrains (Table 16). This means that flexible or rigid arches portray similar variability between terrains.

*Table 16: Standard deviations (SD) of high and low FF feet responses per walking characteristic combining all trials for all three terrain types*, and P-values comparing these standard deviations. All P-values are > 0.05, showing that foot structure does not statistically significantly influence adaptability. a: Wilcoxon test was employed as the data did not follow a normal distribution. *Lateral Neutral Pronation values are based on the trials obtained on Developed and Natural terrain, as this data was not available for the Plate data.*

| | Left high FF feet (SD) | Left low FF feet (SD) | P-value T-test left feet | Right high FF feet (SD) | Right low FF feet (SD) | P-value T-test right feet |
|---|---|---|---|---|---|---|
| **Pace (min km$^{-1}$)** | 2.44 | 2.08 | 0.356 | 3.32 | 2.22 | 0.215 |
| **Cadence (spm)** | 5.58 | 5.29 | 0.717 | 5.97 | 6.58 | 0.529 |
| **Step length (m)** | 0.08 | 0.08 | 0.443[a] | 0.09 | 0.08 | 0.737[a] |
| **Neutral Pronation (%)** | 12.97 | 11.29 | 0.676 | 15.83 | 11.57 | 0.291 |
| **Lateral Neutral Pronation (%)** | 14.28 | 12.70 | 0.765 | 14.47 | 18.71 | 0.486 |
| **Footstrike total (%)** | 5.43 | 5.97 | 0.708 | 6.56 | 5.71 | 0.448 |
| **Rear Footstrike (%)** | 5.28 | 6.48 | 0.514 | 7.62 | 6.72 | 0.479 |
| **Velocity (ms$^{-1}$)** | 0.16 | 0.17 | 0.636 | 0.20 | 0.17 | 0.382 |

Furthermore, the difference in overall average outcomes per walking variable between terrain pairs was calculated for the high FF feet and low FF feet separately (Δresponse) (subtracting the secondly mentioned terrain type from firstly mentioned terrain type) (Table 17). For these calculations, mean participant values were used again and averaged for the five highest and lowest FF feet. Then, the difference in Δresponse between high FF feet and low FF feet was calculated (subtracting low FF Δresponse from high FF Δresponse) (Table 18). Table 18 shows the size of the difference between how low FF feet adapt to two varying terrains and how high FF feet adapt. The difference in Neutral Pronation adaptability between high and low FF feet shown in Table 18 is shown to be much lower than 1 SD of dynamic response when taking all participants into consideration (Table 19). This means that when looking at adaptability between terrain changes between foot structures, Neutral Pronation shows a very low variability, i.e., difference in Neutral Pronation experienced by high or low FF feet due to a change in terrain is lower than the general variability experienced in Neutral Pronation.

*Table 17: Δresponse between terrains for low FF feet and high FF feet. Values were calculated for each walking characteristic as follows: the mean values for the five participants with low or high FF feet were averaged. The average value associated with the second mentioned terrain was subtracted from the first mentioned terrain. For example (1): low FF right feet walk at a slower pace of 3.80 min/km on the Plate than on Developed terrain. For example (2): for low FF left feet, Neutral Pronation occurs for 2.40% of steps more on the Plate than on Developed terrain.*
*Rear Footstrike (%) values are representative of the corresponding lateral side, all other walking characteristics are not lateral-side specific.*

| | **Right feet** | **Pace (min km$^{-1}$)** | **Cadence (spm)** | **Step length (m)** | **Neutral Pronation (%)** | **Footstrike total (%)** | **Rear Footstrike (%)** | **Velocity (ms$^{-1}$)** |
|---|---|---|---|---|---|---|---|---|
| **Plate - Developed** | Low FF | 3.80 | 0.34 | -0.16 | 9.49 | -9.88 | -10.58 | -0.29 |
| | High FF | 6.02 | -4.98 | -0.19 | 13.78 | -12.30 | -12.03 | -0.41 |
| **Plate - Natural** | Low FF | 2.54 | 6.22 | -0.13 | 4.98 | -8.25 | -8.97 | -0.19 |
| | High FF | 4.50 | 0.90 | -0.15 | 12.82 | -9.78 | -9.43 | -0.27 |
| **Developed - Natural** | Low FF | -1.26 | 5.88 | 0.03 | -4.51 | 1.63 | 1.61 | 0.10 |
| | High FF | -1.52 | 5.88 | 0.04 | -0.96 | 2.52 | 2.60 | 0.14 |

| | **Left feet** | **Pace (min km$^{-1}$)** | **Cadence (spm)** | **Step length (m)** | **Neutral Pronation (%)** | **Footstrike total (%)** | **Rear Footstrike (%)** | **Velocity (ms$^{-1}$)** |
|---|---|---|---|---|---|---|---|---|
| **Plate - Developed** | Low FF | 3.52 | -0.40 | -0.16 | 2.40 | -11.64 | -11.56 | -0.31 |
| | High FF | 4.80 | -1.84 | -0.16 | 9.47 | -10.42 | -10.13 | -0.31 |
| **Plate - Natural** | Low FF | 2.31 | 4.84 | -0.13 | 12.28 | -10.96 | -11.02 | -0.22 |
| | High FF | 3.30 | 2.92 | -0.11 | 10.24 | -8.51 | -8.54 | -0.17 |
| **Developed - Natural** | Low FF | -1.22 | 5.24 | 0.02 | 9.88 | 0.68 | 0.54 | 0.10 |
| | High FF | -1.50 | 4.76 | 0.05 | 0.77 | 1.92 | 1.59 | 0.14 |

*Table 18: The difference in ∆response between high FF feet and low FF feet (subtracting low FF ∆response from high FF ∆response). For example: high FF right feet change 4.29% (∆response) more in Neutral Pronation between Plate and Developed terrain than low FF right feet. *The '%' reflects the percentage of steps that have resulted in the Neutral Pronation range; the '%' does not reflect a relative number between two situations. Rear Footstrike (%) values are representative of the corresponding lateral side, all other walking characteristics are not lateral-side specific.*

| **Right feet** | **Pace (min km$^{-1}$)** | **Cadence (spm)** | **Step length (m)** | **Neutral Pronation (%)** | **Footstrike total (%)** | **Rear Footstrike (%)** | **Velocity (ms$^{-1}$)** |
|---|---|---|---|---|---|---|---|
| **Plate - Developed** | 2.22 | -5.32 | -0.03 | **4.29** | -2.42 | -1.45 | -0.12 |
| **Plate - Natural** | 1.95 | -5.32 | -0.02 | **7.84** | -1.52 | -0.46 | -0.08 |
| **Developed - Natural** | -0.26 | 0.00 | 0.02 | **3.55** | 0.90 | 0.99 | 0.04 |
| | | | | | | | |
| **Left feet** | **Pace (min km$^{-1}$)** | **Cadence (spm)** | **Step length (m)** | **Neutral Pronation (%)** | **Footstrike total (%)** | **Rear Footstrike (%)** | **Velocity (ms$^{-1}$)** |
| **Plate - Developed** | 1.28 | -1.44 | -0.002 | **7.07** | 1.22 | 1.43 | 0.002 |
| **Plate - Natural** | 0.99 | -1.92 | 0.03 | **-2.04** | 2.45 | 2.48 | 0.05 |
| **Developed - Natural** | -0.28 | -0.48 | 0.03 | **-9.11** | 1.24 | 1.05 | 0.05 |

*Table 19: Standard deviations for all mean participant values per variable and terrain type.*

| | **Pace (min km$^{-1}$)** | **Cadence (spm)** | **Step length (m)** | **Neutral Pronation (%)** | **Footstrike total (%)** | **Left rear Footstrike (%)** | **Right rear Footstrike (%)** | **Velocity (ms$^{-1}$)** |
|---|---|---|---|---|---|---|---|---|
| **Plate** | 2.6 | 5.9 | 0.058 | 30 | 3.8 | 4.2 | 3.7 | 0.13 |
| **Developed** | 1 | 5.7 | 0.0042 | 35 | 0.36 | 0.45 | 0.46 | 0.11 |
| **Natural** | 1.4 | 5.7 | 0.0051 | 31 | 2.1 | 1.5 | 2.9 | 0.13 |

### 3.3.3. Dynamic response of the foot to different terrain types

The foot's dynamic response to terrain is investigated by comparing values for Power, Cadence, Step length, Neutral Pronation, Footstrike and Velocity for walking trials on the Plate, Developed, and Natural terrains. These values indicate whether terrain influences walking characteristics.

It is found that generally the foot's dynamic response changes with terrain. More specifically, Step length, Footstrike and Velocity are all significantly different depending on whether an individual walks on a lab-based pressure Plate, or outside on Developed terrain or Natural terrain (Table 20). Power is found to significantly differ between Developed and Natural terrain (P = 0.044), and Cadence is found to differ significantly between Developed and Natural terrain (P = 2.4e-05), as well as Plate and Natural terrain (P = 0.04). Neutral Pronation indicated a statistically significant difference between the three terrains following the ANOVA test, but did not yield significant differences in the post-hoc comparisons between any terrain pairs ($P \geq 0.092$). In conclusion, it is found that terrain influences one's walking characteristics, with the exception of Neutral Pronation.

*Table 20: An overview of 21 comparative calculations comparing the medians and means of walking characteristics between the varying terrain. The description column indicates the characteristics that are compared, the P-values are shown and signal the applied test: [a]: repeated measures ANOVA test, [b]: Friedman ANOVA, [c]: Pairwise paired T-test, [d]: pairwise Wilcoxon signed-rank test. The Terrain pairs column specifies which two terrains are compared in the Pairwise calculation column. The yellow fields indicate 'final' statistically significant outcomes, which means that a statistically significant difference is found for that characteristic between the terrains. Power only compares Natural with Developed; Plate data was not available.*

| **Description** | **P-value paired T-test** | | |
|---|---|---|---|
| Power | 0.044 | | |
| | **P-value ANOVA** | **P-value Pairwise** | **Terrain pairs** |
| Cadence | 2.4e-05[a] | 0.09[c] | Plate/Developed |
| | | 2.4e-05[c] | Developed/Natural |
| | | 0.04[c] | Plate/Natural |
| Step length | 5.5e-15[a] | 1.8e-09[c] | Plate/Developed |
| | | 5.6e-04[c] | Developed/Natural |
| | | 2.4e-07[c] | Plate/Natural |
| Neutral Pronation | 4.0e-04[b] | 0.860[d] | Plate/Developed |
| | | 1.0[d] | Developed/Natural |
| | | 0.092[d] | Plate/Natural |
| Footstrike | 1.8e-07[b] | 4.6e-05[d] | Plate/Developed |
| | | 2.2e-03[d] | Developed/Natural |
| | | 9.2e-05[d] | Plate/Natural |
| Velocity | 7.0e-13[a] | 1.3e-08[c] | Plate/Developed |
| | | 6.1e-05[c] | Developed/Natural |
| | | 1.3e-05[c] | Plate/Natural |

*Table 21: Correlation coefficients between walking characteristics within a terrain, and between terrain types within a characteristic. Strong and significant correlations are indicated by a bold font in yellow fields, moderately strong and significant correlations are indicated by a bold font in neutral fields, weak associations are shown in normal font, and insignificant associations are shown in grey. Plate (P), Developed (D), Natural (N), Power (W), Cadence (C), Step length (S), Neutral Pronation (PN), Footstrike total (FT), Velocity (MS).*
*A complete overview of correlation calculations including their respective P-values can be found in Appendix 16.*

| (a) | PS | PPN | PFT | PMS |
|---|---|---|---|---|
| **PC** | 0.28 | -0.02 | -0.36 | **0.61** |
| **PS** | N/A | -0.11 | **0.58** | **0.92** |
| **PPN** | | N/A | 0.12 | -0.18 |
| **PFT** | | | N/A | 0.32 |

| (b) | DC | DS | DPN | DFT | DMS |
|---|---|---|---|---|---|
| **DW** | -0.17 | 0.02 | 0.41 | -0.06 | 0.02 |
| **DC** | N/A | 0.19 | -0.38 | 0.49 | **0.73** |
| **DS** | | N/A | 0.04 | 0.47 | **0.77** |
| **DPN** | | | N/A | -0.23 | -0.27 |
| **DFT** | | | | N/A | **0.65** |

| (c) | NC | NS | NPN | NFT | NMS |
|---|---|---|---|---|---|
| **NW** | -0.28 | -0.18 | 0.27 | -0.15 | -0.27 |
| **NC** | N/A | 0.31 | -0.4 | 0.18 | **0.71** |
| **NS** | | N/A | -0.2 | 0.08 | **0.89** |
| **NPN** | | | N/A | -0.19 | -0.31 |
| **NFT** | | | | N/A | 0.1 |

| (d) | PC | DC |
|---|---|---|
| **DC** | **0.67** | N/A |
| **NC** | **0.69** | **0.79** |

| (e) | PS | DS |
|---|---|---|
| **DS** | **0.5** | N/A |
| **NS** | 0.48 | **0.76** |

| (f) | PPN | DPN |
|---|---|---|
| **DPN** | **0.85** | N/A |
| **NPN** | **0.8** | **0.86** |

| (g) | PFT | DFT |
|---|---|---|
| **DFT** | **-0.54** | N/A |
| **NFT** | -0.2 | 0.27 |

| (h) | PMS | DMS |
|---|---|---|
| **DMS** | 0.44 | N/A |
| **NMS** | **0.55** | **0.63** |

Building on the knowledge that dynamic response varies with terrain, correlation coefficients were calculated to establish whether trends within walking characteristics were upheld between terrains, as well as whether relationships could be established between walking characteristics within a particular terrain (Table 21). Consistently strong, positive associations between two walking characteristics are limited to Velocity with Cadence and Step length (Table 21a-c). Power and Pronation are not correlated with any other characteristics. Other moderate or weak associations are not consistently observed and thus do not allow for conclusions to be drawn. As for associations between terrains per walking characteristic, it is observed that Neutral Pronation values are strongly and positively correlated between all three terrains (Table 21f). Additionally, it is observed that three strong associations and one moderate association make up four out of five possible relationships between Developed and Natural terrain (Table 21d-h). This means that walking characteristics between these two terrains have a clearer linear relationship than between Plate and Developed (one strong, three moderate associations) and Plate and Natural (one strong, two moderate). Lastly, Footstrike yields a moderate association with Step length and

Velocity, (Table 21a) but as this only occurs in one out of three terrains, this cannot be stated as a meaningful outcome.

All in all, the walking characteristics examined suggest the foot’s dynamic response changes with terrain, with the exception of pronation, which seems to be inherent to the foot irrespective of terrain or other walking characteristics. Additionally, Velocity yielded strong correlations with Step length for all terrain types and strong and moderate correlations with Cadence. No further relationships between the tested walking characteristics could be established.

### 3.3.4. Foot biophysics – relationship between FF, displacement, spring constant and spring energy

The relationship between Foot Flexibility, arch displacement, arch spring constant and arch spring energy is elucidated through correlations between these variables. The relationship between arch flexibility and energy storage is visualised.

The Shapiro-Wilk test was employed to test whether the variables follow normal distributions, appropriate statistical tests were subsequently used.

Paired statistical tests subsequently showed that the means (T-test) and medians (Wilcoxon) of the variables were not statistically significantly different between the left and right feet, except for the horizontal spring constant. This means that the displacements along both the horizontal and vertical axes, the vertical spring constant and the spring energies all have similar means/medians for the left and right feet.

Correlations between variables were tested to elucidate the relationship between arch displacement (x), Foot Flexibility, the spring constant (k) and the spring energy (E) (Table 22). Strong and significant correlations were only found in the vertical direction, where an increase in FF (stiffer arch) was logically found to be associated with a lower magnitude of vertical arch displacement (arch lowering) (Figure 20) and spring energy (Figure 22), and associated with a greater spring constant. An increase in arch lowering was found to be associated with a lower spring constant. There were three moderate and significant correlations found in the horizontal direction, where a higher FF value was found to be associated with less arch lengthening (Figure 21) and increased spring energy (Figure 23), and an association was found between arch lengthening and a lower magnitude spring constant. Other calculations yielded weak and insignificant correlations in the horizontal direction and when comparing the horizontal and vertical spring constant (Table 22). These results reveal that biophysical aspects in the vertical direction are more consistent and indicative of arch mobility than those measured in the horizontal direction (Figure 24). A higher FF value (less arch deformation) is associated with an arch drop of smaller magnitude, a greater spring constant and less spring energy. Foot Flexibility is shown to influence the biophysics of the foot when going from sitting to standing position in terms of energy storage with weight change.

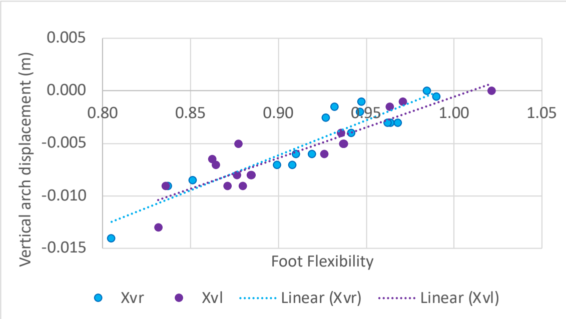


*Figure 20: Plotting Foot Flexibility and vertical arch displacement, shows a strong, positive linear relationship.*

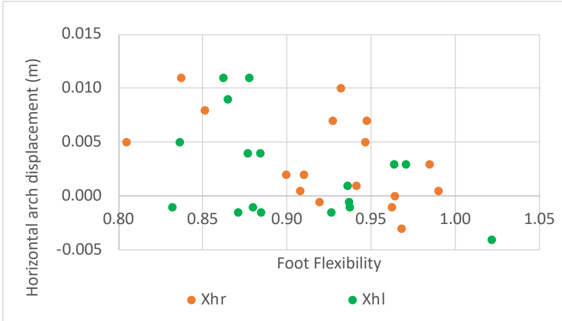


*Figure 21: Plotting Foot Flexibility and horizontal arch displacement shows moderate – no distribution.*

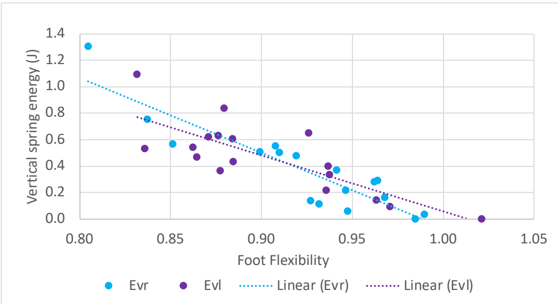


*Figure 22: Plotting Foot Flexibility and vertical spring energy shows a strong, negative linear relationship.*

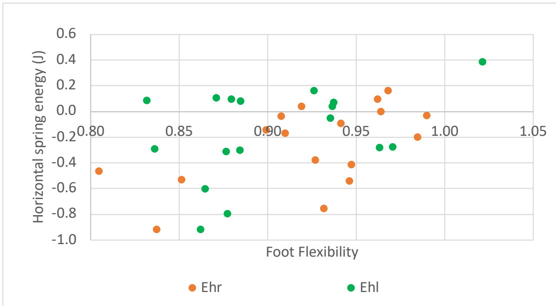


*Figure 23: Plotting Foot Flexibility and horizontal spring energy shows moderate - no distribution.*

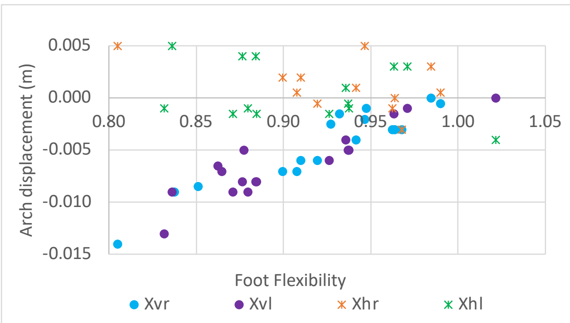


*Figure 24: The relationship between FF and vertical arch displacement is linear, whereas the relationship between FF and horizontal arch displacement is disorganised.*

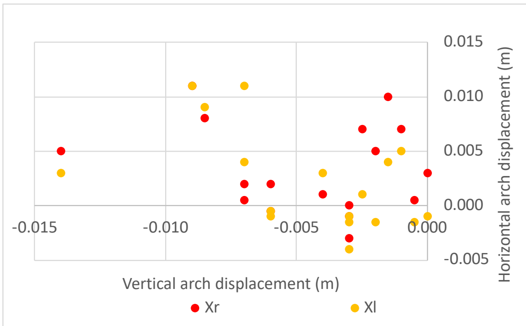


*Figure 25: No correlation is observed between vertical and horizontal arch displacement when going from sitting (10% WB) to standing position (50% WB).*

*Table 22: An overview of correlations is shown between the anthropometric FF and biophysical aspects of the arch. The columns show the direction of the biophysical measures, the two aspects being compared, the lateral side of the measurement, and the two specific variables being compared. The strength of the correlation and the significance level associated with the correlation are found in the Correlation coefficient and P-value column, respectively. The textual conclusion of these two values can be found in the last column. The variables can be separated into three parts (two for the FF): the category, the direction and the lateral side. The abbreviations (first part): Foot Flexibility (FF), arch displacement (X), spring constant (K), spring energy (E); vertical (v) and horizontal (h) (second part); and right (r) and left (l) (third part).*
*[a]: Pearson correlation test, [b]: Spearman correlation test*

| **Direction** | **Category** | **Lateral side** | **Variables** | **Correlation coefficient** | **P-value** | **Strength of association and significance** |
|---|---|---|---|---|---|---|
| **Vertical** | FF - displacement | Right | **FFr - Xvr** | 0.93 | 4.4e-09[a] | Strong association, significant |
| | | Left | **FFl - Xvl** | 0.91 | 5.9e-07[a] | Strong association, significant |
| | FF - spring constant | Right | **FFr - Kvr** | 0.86 | < 2.2e-16[b] | Strong association, significant |
| | | Left | **FFl - Kvl** | 0.77 | 8.0e-04[b] | Strong association, significant |
| | Displacement - spring constant | Right | **Xvr - Kvr** | 0.96 | 3.9e-09[b] | Strong association, significant |
| | | Left | **Xvl - Kvl** | 0.89 | 3.2e-06[b] | Strong association, significant |
| | FF - spring energy | Right | **FFr - Evr** | -0.87 | 2.2e-16[b] | Strong association, significant |
| | | Left | **FFl - Evl** | -0.80 | 1.3e-04[a] | Strong association, significant |
| | | | | | | |
| **Horizontal** | FF - displacement | Right | **FFr - Xhr** | -0.51 | 0.037[a] | Moderate association, significant |
| | Displacement - spring constant | Left | **Xhl - Khl** | -0.53 | 0.029[b] | Moderate association, significant |
| | FF - spring energy | Right | **FFr - Ehr** | 0.56 | 0.020[a] | Moderate association, significant |
| | | | | | | |
| **Horizontal** | FF - displacement | Left | **FFl - Xhl** | -0.41 | 0.103[b] | Weak association, not significant |
| | FF - spring constant | Right | **FFr - Khr** | -0.04 | 0.869[a] | Weak association, not significant |
| | | Left | **FFl - Khl** | -0.03 | 0.897[a] | Weak association, not significant |
| | Displacement - spring constant | Right | **Xhr - Khr** | -0.03 | 0.898[a] | Weak association, not significant |
| | FF - spring energy | Left | **FFl - Ehl** | 0.41 | 0.107[a] | Weak association, not significant |
| | Vertical - horizontal spring constant | Right | **Kvr - Khr** | -0.06 | 0.832[b] | Weak association, not significant |
| | | Left | **Kvl - Khl** | -0.19 | 0.477[b] | Weak association, not significant |

No statistically significant associations were found between bodyweight and arch deformation or between Foot Flexibilities between the left and right feet (Table 24 in section 3.4). As can be expected based on the lack of relationship between the vertical and horizontal values for the spring constant (Table 22), no relationships were found between the vertical and horizontal values for arch displacement (Figure 25) and spring energy (Table 24 in section 3.4).

## 3.4. Discussion

Investigating the relationships of terrain with foot structure and with dynamic response, as well as the relationship of foot structure with the foot's immediate adaptability and with biomechanics has resulted in insight into these, and related, relationships.

No relationships could be established between terrain and Foot Flexibility; neither between youth terrain and FF in adults (section 3.3.1), nor any correlation between FF and the foot's walking characteristics (section 3.3.2). This means that youth terrain does not affect the foot's structure into adulthood, nor does foot structure influence walking characteristics on a specific terrain or the level of immediate adaptability between two different terrains. Besides the lack of trend regarding structural morphology, for dynamic response it was found that the expression of walking characteristics differs depending on the terrain walked upon. Power, Cadence, Step length, Footstrike and Velocity all yield statistically significantly different outcomes for different terrains (exception: Cadence Plate/Developed) (section 3.3.3). The body's adjustment to terrain during walking does not extend to Pronation, however, as pronation appears to be a characteristic intrinsic to the foot. Pronation does not yield statistically significantly different results between terrains and, additionally, strong and positive linear relationships can be observed between the three terrains. Since Velocity is calculated based on Step length and Cadence, positive linear relationships can be observed between Velocity and Step length, and Velocity and Cadence. The walking characteristics do not seem to be otherwise interrelated. Regarding the relationship of foot structure and the biophysics of the foot, the relationship between Foot Flexibility and vertical movement of the arch is much stronger and clearer than horizontal movement of the arch. A more flexible arch (low FF) is associated with a higher spring energy, suggesting that more energy is transferred in the arch of a flexible foot (section 3.3.4).

### *Experimental design*

All data collected originates from seventeen participants from a convenience sample. This population size was considered sufficient for the purpose of this study; however, a larger sample size would increase the substance of the results. The sample consisted of a fair balance of sexes, and included a variety of nationalities; however, the majority of the participants was white, meaning that the results may be biased and not accurately reflective of the cross-section of the UK population.

Initially, the RS Footscan pressure plate data was intended to be used to verify insole data and foot dimensions, as well as to gain insight into the relationship of plantar pressure between shod and barefoot walking. Future work could examine the collected data for similarities and discrepancies between the Insole data and RS Footscan data to address the gap in available knowledge due to limited data collection abilities, as insoles can only collect data while shod, and the pressure plate is typically used on a flat surface.

A few setbacks were encountered during the process of collecting the data using the insoles. The trials collected on the Plate were short (average 14 seconds) compared to trials collected on Developed and Natural terrain (average 63 seconds in both instances). This, coupled with the fact that the path followed for Plate measurements was not fully uninterrupted and had two turning moments, could compromise the participants' natural-walking flow and the substance of the data. Additionally, the gaps in the data due to technology malfunctioning are also expected to influence the outcomes. However, as multiple trials were performed per participant, only the data regarding lateral side Pronation and lateral side Footstrike, for Natural and Developed data for one participant, and Developed data for another participant, are based on single trials. All remaining datapoints are averages from at least two trials.

As, during walking, the arch of the foot deforms and returns to its natural shape without damage, it can be assumed that the arch follows Hooke's law[71]. This would allow calculation of the spring constant and subsequently spring energy in each dimension of arch deformation. However, as the arch's movement is three dimensional, it is plausible that the arch deforms differently in each dimension depending on a number of variables, such as footstrike, balance, terrain and velocity. The equations regarding Hooke's law and spring energy (Equations 5 and 6) are based on the assumption that the biophysics of the foot functions as an ideal system.

In accordance with the data collection design, participants first completed lab-based data collection followed by Developed terrain and Natural terrain. Fatigue could have influenced the data collected at the Natural terrain stage, although this is not expected as all participants were healthy and exercised regularly.

### *Youth terrain and adult FF*

Based on the findings of Chapter 2, it was expected that people who have grown up on Natural terrain would have more flexible arches, even into adulthood, although possibly with diminishing effect. However, no evidence was found to support that this association between youth terrain and adult FF persists. This could suggest that the structural development of the arch is indeed continuous beyond the age of 11 years[52]. It seems likely that the lack of relationship between static measurement in adulthood and youth terrain is due to participants having lived in various areas with different terrain types. Future work could perform static measurements with people who have lived on one type of terrain for the majority of their lives, to see if the trend does persist without long term exposure to a different terrain type. Additionally, the timeframe in which feet adapt to new terrain could be investigated.

From the AHI data stated in Table 1, a mean FF of 0.94 can be calculated. The average FF values from the participants in this study are 0.90 for left feet and 0.92 for right feet. These are slightly lower than the mean value based on literature.

### *The relationship between foot structure and interaction with terrain*

It was expected that foot structure (arch flexibility) would influence the foot's behaviour while walking, particularly the Pronation values and possibly Footstrike to accommodate shock absorption. However, only a few statistically significant outcomes were observed, none of which were present consistently enough to draw a conclusion between FF and walking characteristics. Although more flexible arches did yield a lower Neutral Pronation percentage (Plate: $P = 0.036$ and Natural terrain: $P = 0.048$), this was only observed in the values associated with data collected from participants in the outer range of FF in left feet (top five and bottom five FFs) and was not also reflected by statistically significant Over or Under Pronation values for either lateral side. This could suggest that more flexible arches do not necessarily over-pronate, nor that stiff arches under-pronate, instead, it is possible that more flexible feet sway more within the full pronation-supination range and that stiff arches remain within the Neutral Pronation range (as determined by Nurvv insoles) more consistently. This is corroborated by the lack of correlation between all FFs and Pronation values (Appendix 15). What is remarkable though, is that this effect of FF on Neutral Pronation is seen for Plate and Natural data, but not for Developed data (Table 15). This could suggest that flexible arches benefit more from their flexibility on Natural terrain than on Developed terrain. Another interesting observation emerging from these results is that four out of five statistically significant results between high and low FF originate from the Plate data (Table 15), and that Plate data has the highest variability for most walking characteristics (Table 19). This suggests that structural differences are more apparent in a clinical setting; participants might walk differently in a controlled setting (when one might be conscious of assessment), or structural differences are compensated for when walking freely. Alternatively, as the time of observation is much shorter on a pressure plate, this provides only an impression of the natural cadence of the individual. Contrastingly, variability is generally lowest for Developed terrain.

### *The relationship between foot structure and immediate adaptation to different terrain*

In general, foot structure showed no impact upon the interaction with terrain; likewise, no difference in adaptability was found between rigid and flexible arches. One questionable feature about the calculation of adaptability is that on two occasions the same participant had one foot falling in the lowest five FFs and the other foot in the highest five FFs. This means that while walking characteristics were compared per lateral side, these values are based on information from both lateral sides. The only exception to this is Rear Footstrike. As lateral side-specific Pronation data is not available for the Plate measurements, these could not be taken into consideration for the calculations. The current data suggests that flexible and rigid arches exhibit unvaried adaptability to terrain (Table 16).

### *Dynamic response of the foot to different terrain types*

The expectation that terrain would influence the walking characteristics, i.e., the foot's dynamic response changes according to terrain, was mostly reflected in the results. Interestingly, Pronation values did not significantly differ between any terrain types (Table 20). From the results obtained in section 3.3.3, pronation appears to be a quality inherent to a foot; independent of terrain or other walking characteristics, supplemented by the fact that Pronation is strongly, positively correlated between all three terrains. This, combined with the results from section 3.3.2 that under- or over-pronation cannot be determined based on FF, also supports the notion that pronation is an independent characteristic of the foot.

Except for measurements of Cadence and Neutral Pronation, statistically significant differences were found between all three terrain types; an implication of which is that measurements collected on a pressure plate do not represent measurements collected when walking in everyday settings. So, while Cadence and Neutral Pronation can be measured clinically to reflect natural patterns, Step length, Footstrike, and Velocity have yielded inconsistent outcomes between Plate and both Natural / Developed terrain, therefore yielding this method of data gathering unsuitable. Future research could benefit from testing this hypothesis on a greater scale, to compare natural patterns to clinically measured patterns.

Both Cadence and Step length have yielded strong, positive correlations between Developed and Natural terrain (Table 21); although their absolute values may differ between terrain types (Table 20), the outcomes between the two terrains are linearly related. The underlying theory that can be proposed is that the foot alters its dynamic response to the terrain it encounters, confirming the study expectations. Consequently, it can be hypothesised that when an individual grows up mostly on a certain terrain, the consistent accommodative dynamic response would result in structural growth and walking characteristics according to that terrain. This could explain the structural consequences of terrain upon the foot and why the relationship between youth terrain and FF is no longer apparent after many years and relocating.

Another observation is that the Footstrike data generally follows a normal distribution, except for Natural terrain (Table 23). For both the left and right feet, the percentage of rear

Footstrike steps follow normal distributions for the Plate and Developed terrain, but not for Natural terrain. For the Total Footstrike, (percentage of rear Footstrike steps averaged for both feet) Natural terrain does not follow a normal distribution, and neither does Developed terrain. This would suggest that, in addition to terrain impacting the walking characteristics' values, Natural terrain influences Footstrike to the point it prevents the following of a normal distribution.

*Table 23: Whether Footstrike values follow normal distributions according to the Shapiro-Wilk test per lateral side and terrain.*

| Description | Terrain | Right feet | Left feet |
|---|---|---|---|
| **Footstrike Total** | Plate | Yes | Yes |
| | Developed | No | No |
| | Natural | No | No |
| **Footstrike Left Rear** | Plate | N/A | Yes |
| | Developed | N/A | Yes |
| | Natural | N/A | No |
| **Footstrike Right Rear** | Plate | Yes | N/A |
| | Developed | Yes | N/A |
| | Natural | No | N/A |

### *Biophysics of the foot*

The exploration of the biophysics of the foot has shown that a more deforming arch does store more energy, primarily due to deformation in the vertical direction. It is found that vertical displacement of the arch is a more determining factor of arch flexibility and energy storage than horizontal displacement (Figure 24 in section 3.3.4).

The lack of correlation between vertical and horizontal arch displacement (Figure 25 in section 3.3.4Table 20) implies that each arch deforms in a unique manner, possibly due to the anatomy of the foot (e.g., bones, ligaments, tendons, and muscles). As the trendlines of the relationships between FF and vertical spring constant (Figure 26), and between arch displacement and the spring constant, appear exponential (Figure 27 andFigure 28) rather than linear, these are not technically correlated (linear association) but have an alternative mathematical relationship[69].

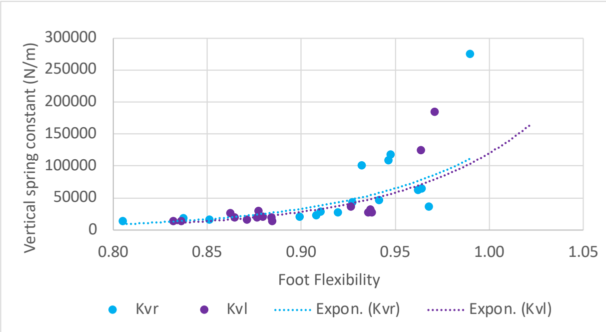


*Figure 26: Non-linear relationship between vertical spring constant and FF.*

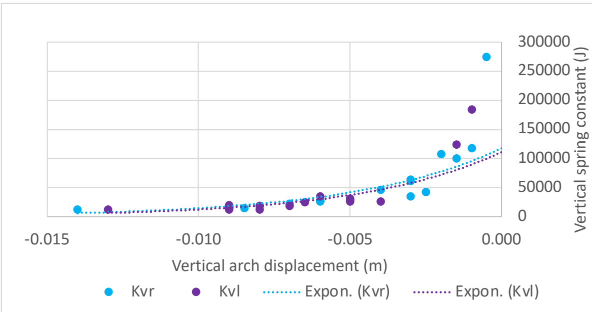


*Figure 28: Non-linear relationship between vertical spring constant and vertical arch displacement.*

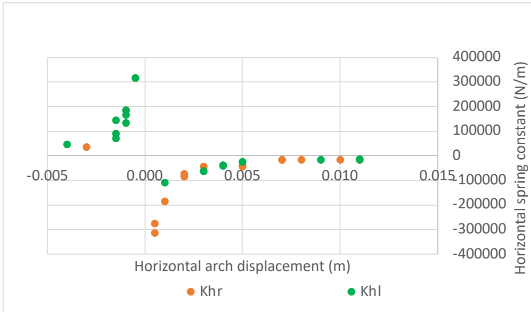


*Figure 27: Non-linear relationship between horizontal spring constant and horizontal arch displacement.*

Additional calculations were performed to determine the presence of correlations between horizontal and vertical displacement, horizontal and vertical energy, left and right FF, and bodyweight to displacement (Table 24). No statistically significant associations could be determined.

*Table 24: Correlations between horizontal and vertical displacement and energy, left and right FF, and body weight and displacement.*

| **Category** | **Lateral side** | **Variables** | **Correlation coefficient** | **P-value** | **Strength of association and significance** |
|---|---|---|---|---|---|
| Vertical vs horizontal displacement | Right | Xhr, Xvr | -0.17 | 0.510 | Weak association, not significant |
| | Left | Xhl, Xvl | -2.5e-03 | 0.992 | Weak association, not significant |
| Vertical vs horizontal energy | Right | Ehr, Evr | -0.24 | 0.346 | Weak association, not significant |
| | Left | Ehl, Evl | 0.10 | 0.708 | Weak association, not significant |
| Left vs right FF | | FFr, FFl | 0.10 | 0.707 | Weak association, not significant |
| Body weight to displacement | Right | BW, Xhr | -0.09 | 0.719 | Weak association, not significant |
| | | BW, Xvr | -0.26 | 0.316 | Weak association, not significant |
| | Left | BW, Xhl | -0.25 | 0.338 | Weak association, not significant |
| | | BW, Xvl | 0.30 | 0.249 | Weak association, not significant |

Some simplifications were applied to facilitate calculations. Firstly, arch movement in the z-direction was not measured and is thus not taken into consideration; the force on the arch spreads unevenly between the three dimensions[72], but for the purposes of this study, the same full amount of force was used in calculations for each dimension. If a realistic proportion of the force was used in the calculations, maybe consistent correlations would have been obtained from the horizontal displacements as well. Furthermore, the force used to determine the spring constant and spring energy was calculated using the static difference in weight placed on the foot going from sitting (10% WB) to standing (50% WB). This means that the spring energy only comments on the energy contained in the arch while standing on both feet, compared to when sitting down. This is not equivalent to a dynamic walking motion, as force applied to a foot while walking is much larger than 50% WB and not linear across the stance phase[73,74]. Even in mid-stance, when the foot is placed most similarly to standing, the force experienced varies considerably[75]. The amount of arch deformation during walking, and in all three dimensions, could not be measured, which has resulted in limited conclusions on the relationship between FF and energy storage during dynamic arch movement.

To summarise, it is found that feet adapt to their environment; both long-term after living on varying terrains and momentarily to the terrain encountered. The type of terrain that an individual has grown up on is no longer reflected in the static measurement of foot structure in adulthood. This study found no relationships between static structure and dynamic function, nor did it find relationships between dynamic variables. As feet show immediate adaptability to terrain, it is deemed reasonable that encountering one terrain type most frequently while in the foot's developmental stage, would influence the structural development over time. Vertical deformation of the arch seems more contributory to energy storage in the arch than horizontal displacement. Multiple aspects of this study have suggested that pronation is inherent to the foot, independent of external factors.
This study has found that data collected on a pressure plate may not be representative of natural walking patterns. Individuals may walk more consciously when stepping on a pressure plate, which could affect both research and clinical data collection.

## 3.5. Limitations: dynamic movement of the arch

There are limitations associated with the research into the relationships between terrain, Foot Flexibility in adulthood and the dynamic movement of the arch, as presented above. In terms of design, the study used a relatively small population of 17 participants and an inexperienced researcher to obtain the static measurements. Some inaccuracies may be present in the measurements leading to the FF values, although as all measurements were obtained by the same researcher, inter-tester variability is eliminated. Furthermore, most walking characteristics investigated were more reflective of gait than the specific morphology and behaviour of the foot. Analysis of more detailed data regarding pronation was intended, but unfeasible due to formatting issues of exported RS Footscan data. Without this data, the extent of over- or under-pronation could not investigated, leaving only the percentage of steps that fell in the Neutral Pronation range as measured by the insoles. Lastly, due to technological limitations, force dissipation through arch could not be studied to elucidate the biophysics of the foot in dynamic motion. The research performed is based on static measurements and simplifications of the biophysics of the foot, yielding limited conclusions.

## 3.6. Future work: dynamic movement of the arch

Future work regarding the dynamic movement of the arch could utilize the data gathered using the pressure plate RS Footscan to build on the current outcomes. More specific measures for pronation and pressure distribution can be analysed and compared between sub-populations as well as compared to the Insole data. If the RS Footscan data and insole Plate data would be compared, uniformity of outcomes between these methods could be evaluated and specific numerical outcomes of the RS Footscan data could be attempted to be superimposed to the insole Plate data. Additionally, this could address the gap in data collection limitations, as insoles can only be used to collect data with shod participants, and that pressure plates are typically used on flat surfaces in a controlled environment. The RS Footscan required a fair amount of calibration to correct the sizing of the pressure maps, which introduced subjectivity. A qualified clinician could be recommended to promote accuracy and limit variability in the pressure map calibration process. Moreover, the pressure plate data could be used to investigate the relationship between arch flexibility and energy absorption within the arch. It would be interesting to see how results using arch drop and/or arch height compare, as arch drop was found to be the most dominating factor in arch flexibility and biophysics.

Further studies could investigate whether there is a difference in walking characteristics between the populations that have grown up on Natural terrain and Developed terrain. Youth terrain and foot structure were found to be unrelated, and foot structure and walking characteristics were found to be unrelated, but it would be interesting to see if patterns from youth can be recognised and distinguished in adulthood. Additionally, future work could investigate over which time-period feet adapt to alternating terrain types. This could be done by investigating the length of substantial time that each participant has spent on each terrain type, or performing static (and dynamic) measurements with participants who have lived on one type of terrain for the majority of their lives. In this way, the boundaries of the relationship between foot structure and (youth) terrain, as well as the foot's adaptability, can be explored. It would also be worthwhile to assess the pathological patterns between participants living on alternate terrains.

As previously touched upon, the field could benefit from more research into the agreement of data collected on a pressure plate in a lab-based setting and from natural walking patterns. As this study has found that clinically measured walking patterns do not accurately represent natural patterns, this method of data gathering may be considered unsuitable. Future research could explore this observation on a greater scale to provide insight into the validity and limitations of clinical measurements. Likewise, a larger study could be performed to confirm the overall results obtained from this study.

Additionally, more research into the precise movement of the arch and the amount of deformation in each dimension during both static and dynamic weight transfer could be performed. This would elucidate the relationships between arch height, arch rigidity, and level of pronation in relation to energy storage. Such knowledge could link arch flexibility, and its impacting factors, to pathology.

Lastly, the effect of varying footwear types and lifestyle behaviours, such as amount and type of physical activity on the movement of the arch could be investigated.

# 4. Conclusions

In conclusion, it is found that feet adapt to their environment; structurally during the developmental age, as well as adjusting in the long term after foot development and immediately through dynamic response to the terrain encountered in the moment. While participants between the ages of 9 – 11 years live on a certain terrain, their foot structures adapt to this terrain, resulting in participants living on Natural terrain having more flexible arches and participants living on Developed + Mixed terrain having more rigid arches. When assessing the Foot Flexibility of adult participants, no relationship is observed between youth terrain and current foot structure. Additionally, no consequences could be established, using smart insoles, from having an either more or less flexible arch when assessing walking characteristics. Pronation seems to be a foot intrinsic quality, unrelated to gait pattern and terrain encountered. Other walking characteristics are not interrelated either, but do differ depending on the terrain walked on. Arch drop is found to be a more significant factor in determining the biophysics of the foot than arch lengthening.

Despite the limitations, the findings of this study were found to be statistically significant. Implementation of the future work suggestions are expected to strengthen the evidence for the relationships and trends observed in the current study.

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# 6. Appendices

BBC TERRIFIC SCIENTIFIC

Teacher Resource

# Feet

## Does environment affect foot flexibility?

Terrific Scientific Campaign

# Investigation 7
# Feet

## Introduction

Our bodies are amazing! They are made up of many different parts that all work together to help us carry out our daily activities. Each part is adapted to carry out a particular function. Our hearts do a great job of pumping blood around our bodies. Our stomachs are really good at breaking down food so that we can get the nutrients we need from it. There are, however, some parts of our body that we take for granted and hardly pay any attention to at all. Now is the time to stop and explore a crucial but overlooked part of our body – our feet. They are vital in enabling us to balance and stand up.

## Background information

All animals and plants are adapted to their habitats. This means they have special features (adaptations) that help them to live, catch their food and survive in their environment. Arctic rabbits have white fur so they can't be easily seen in the snow by things that might eat them. Cheetahs have long, strong legs so they can run fast and catch their prey. And whales have thick layers of blubber to keep them warm in the cold seas.

Sometimes the environment can cause changes in an individual animal living within it; if an animal lives in an area with lots of food it will grow bigger than it would if it lived in an area with very little food! These changes aren't quite the same as adaptations like fur or long legs, they aren't passed down from parent to child, but they are just as important for survival!

BBC TERRIFIC SCIENTIFIC

## Related links:

Find out more about adaptation and inheritance here:

bbc.co.uk/education/topics/zvhhvcw

Our feet help us to balance, run and walk and they can be flexible or inflexible. The shape and structure of human feet are an adaptation to walking upright on two legs, but scientists think that changes to their flexibility are caused by the environment we live in.

Scientists from the University of Kent want to investigate how the environment affects foot flexibility. Their theory is that children who spend more time playing on even surfaces will have less flexible feet than children who spend time playing on uneven surfaces. The results gathered by the children during this Terrific Scientific activity will give a much better idea as to whether this hypothesis is true.

In this series of activities, the children are going to be taking measurements of their feet. The scientists at the University of Kent will use this information, together with information about the type of terrain on which the children spend most of their time, to see if there is a link between their range of foot flexibility and the local environment.

# These activities encourage children to:

- **Take accurate measurements** of their feet.
- **Learn** how to manipulate these measurements to calculate their foot flexibility.
- **Look** for patterns in their data.

**Expected duration:** 2 hours

## Cross-curricular links:

Find out more about our cross-curricular links here on step 5.

bbc.co.uk/guides/z9fjrwx

As well as these key Working Scientifically principles, we have made sure there are links to the science curriculum for each nation, as well as cross-curricular opportunities for further learning. We think these are just as important, as they help to explain the relevance of science and how it links to the world around us.

On our website you will find a supporting 'How to' film which shows teachers and teaching assistants how to set up and carry out the experiment. You will also find additional resources including a step-by-step lesson presentation and an introductory film, which sets the investigation into context for your students.

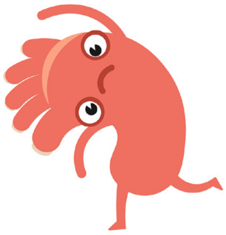
We have partnered with the University of Kent for this investigation.
Your class findings will help further their scientific learning and give input to professional scientific research; understanding the impact of the terrain in the UK on foot flexibility in the UK's primary schools.

**We hope this inspires you and your students to get scientific and we look forward to seeing your results!**

The Terrific Scientific Team.

Supported by: The University of Kent, Royal Society of Biology and Primary Science Quality Mark.

# Contents



# Children will show evidence of learning by:

- Making and recording accurate measurements of their feet.
- Using their results to work out their foot flexibility.
- Looking at patterns in the data linking foot flexibility and surfaces walked on.
- Explaining how animals are adapted to suit their environment.

# What will the children learn? (England, Scotland, Wales, Northern Ireland)

## England

### Working scientifically

- Taking measurements, using a range of scientific equipment, with increasing accuracy and precision, taking repeat readings where appropriate. P177
- Recording data and results of increasing complexity using scientific diagrams and labels, classification keys, tables, scatter graphs, bar and line graphs. P177
- Reporting and presenting findings from enquiries, including conclusions, causal relationships and explanation of and degree of trust in results. P177

### Evolution and inheritance

- Identify how animals and plants are adapted to suit their environment in different ways and that adaptation may lead to evolution. P184
- Recognise that living things have changed over time and that fossils provide information about living things that inhabited the Earth millions of years ago. P184

## Scotland

### Science experiences and outcomes

- Develop the skills of scientific enquiry and investigation using practical techniques. P2
- Develop skills in the accurate use of scientific language, formulae and equations. P2

### Inheritance

- By exploring the characteristics offspring inherit when living things reproduce, I can distinguish between inherited and non-inherited characteristics. SCN 2-14b P15

## Wales

### Skills - Planning

- Decide upon the observations or measurements that need to be made. P13a5
- Decide upon the equipment and techniques required for the enquiry. P13a6
- Make careful observations and accurate measurements, using digital and ICT equipment at times. P13b2
- Make comparisons and identify and describe trends or patterns in data and information. P13b4

### Skills – Reflecting

- Deciding whether the approach/method was successful. P13b2

## Northern Ireland

### Place

- Examine and collect real data. P85
- Investigating similarities and differences, patterns and change. P85
- Explore how place influences the nature of life. P85

# Preparing for the investigation

These activities can be used to stimulate your students to be more curious about their feet, to look at them more closely and to consider how their feet vary.

- Ask the children to look at their own hands and feet and identify what they have in common and what is different about their hands and feet. They can gather their ideas onto the compare and contrast sheet.
- Ask the children, in pairs, to think about what they could measure to record their foot dimensions. Allow them time to take these measurements and record them on diagrams.
- Ask them to compare their foot measurements with their partners'. Can they spot any patterns? If they think they spot a pattern they can check if other people's data supports their pattern. For example, do people with longer feet have longer toes?

The children will now be aware that whilst their feet have common features they are also different. The scientists at the University of Kent are interested in the variation of foot flexibility. This flexibility will vary from person to person and may also vary for one person over time due to changes in the local terrain.

We tend to think of this as how well you can point your toes, but the foot flexibility that the scientists want us to measure is different – it is a comparison of the shape of the foot when standing and sitting. This change is very small so it is really important that measurements are taken really precisely.

**Ask:**

Pupils to think about what they could measure to record their foot dimensions.

Can they spot any patterns?

# Health & safety

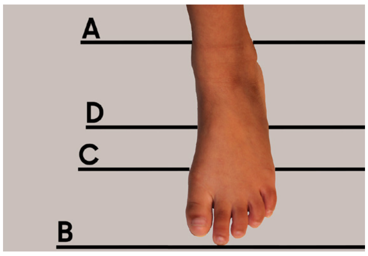
This activity should be done inside. The activity should be risk assessed by the responsible teacher, and the identified control measures must be put in place before any pupil takes part in the activity. Precautions should be taken, as they would be in any similar activity run at the school. It is the responsibility of the teacher to manage this activity safely. In addition, please consider the following advice below.

- The children can leave their socks on if they prefer.
- Children should wash their hands after the activity.
- Warn the children that if the fire alarm sounds they do not stop to put their shoes on.
- Ensure the children do not push the ruler too hard under the ball of the foot.
- Ensure the children move carefully around the classroom when their shoes are off.

**Important!**

It is the responsibility of the teacher to manage this activity safely.

# Activity 1 – Taking foot measurements




## Equipment needed (for each pair of students):

- 2 x sheets of A4 Paper.
- 1 x pencil.
- 2 x 30cm rulers (with square edges).
- Calculator (for Arch Height Index).
- Student worksheet. See step 7 here:

bbc.co.uk/guides/9fjrwx

**Related links:**

The 'how-to' film on our website will really help you to understand how to carry out the investigation bbc.co.uk/guides/zwfp7p3

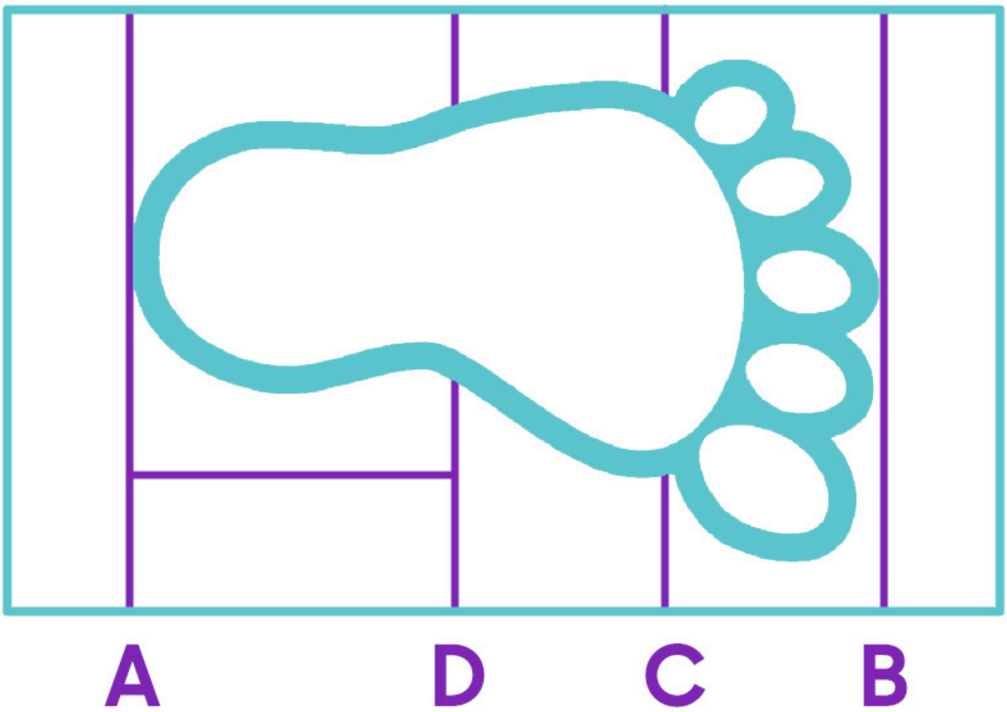
# Method / procedure

- Split the class to work in pairs (assign student 1 and student 2).
- Ask children to take their shoes and socks off (any children who wish to keep their socks on can, as long as they are still able to lift their toes).

# Measurements

- If the 0 cm mark is not at the bottom of the ruler you will need to do the following to get the correct height of the foot.
- Measure how far the 0cm mark is from the bottom of the ruler; **record this on the student worksheet.**
- You will need to add this number to the height to get the accurate **calculated height of the foot.**
- For example if the 0 cm mark is 4mm from the start of the ruler you will need to add 4mm to the height you measured. **Please remember to add this measurement on when you record the height.**

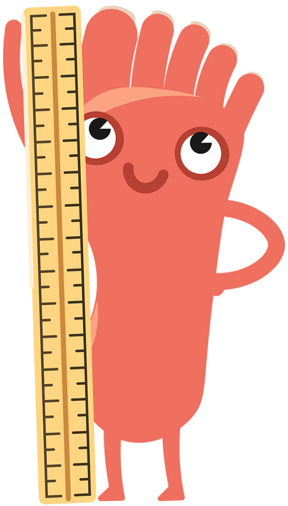
# Plan view of left foot.




Place your ruler on the paper parallel to the shorter edge. Use your ruler to draw a straight line across the width of the paper. This should be the width of the ruler away from the edge.

Label this line, A.

1. Student 1 stands up and places their LEFT foot on the paper, parallel to the edge of the paper, taking care to line their heel up with Line A - making sure it touches it but isn't over the line. Placing the long edge of a ruler on the line and standing it up on its edge can provide a surface for the foot to be backed up to. When the foot is in the correct position ensure they are standing up straight with their arms by their sides, feet a shoulder width apart and heel touching this line. Make sure the student's centre of gravity is over their feet, i.e. they're not leaning forwards or backwards.



2. Student 2 should draw another straight line in line with the top of the longest toe. The longest toe is not always the big toe. Label this B.

3. Without removing Student 1's foot from the paper, carefully measure the distance between A and B and record it on your sheet.

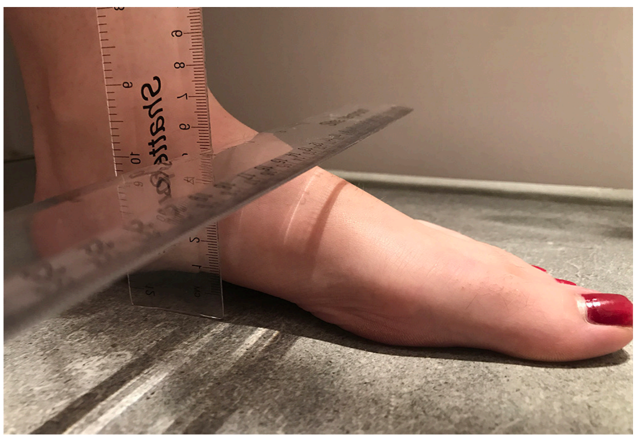
4. Calculate the midpoint between A and B, by dividing this measurement in half.

5. Use your ruler to measure and draw another straight line exactly at the midpoint. Line D on the diagram above. This is also labelled on the student worksheet.

6. Student 2 will now measure the height of Student 1's foot, stand one ruler next to the inside of the foot precisely on the midpoint line, D, you have marked. One side of the ruler must touch line D and the other should be closest to line A (see picture). Hold a second ruler on the top of the foot parallel to the floor and where it touches the upright ruler on the midpoint is the height of the foot. This will help you make an accurate measurement. Record this measurement on the pupil-recording sheet.

**Tip:**

When taking the standing measurement make sure students are stood with their feet a shoulder width apart.



## Don't forget:

The 'how-to' film on our website will really help you to understand how to carry out the investigation bbc.co.uk/guides/zwfp7p3

7. Now ask Student 1 to lift up their toes a little. Slide the ruler under their toes until you feel it touch the ball of their foot. Be gentle so you do not hurt their foot. Use this ruler to draw another straight line (parallel to the short edge of the paper here) label it C.

8. Carefully measure the distance between Line A and Line C. Pupils should write this down on their worksheet.

9. Once you have all your measurements, repeat this method in full but with a new piece of paper and Student 1 sitting down while you do it. Make sure their foot is relaxed when measurements are taken.

10. Finally repeat all of this above for Student 2 both standing and sitting. Watch the How To Film here: bbc.co.uk/guides/zwfp7p3

**Distance from bottom of ruler to 0 cm=__________mm**

| | Distance A to B (mm) | Height of foot (mm) | Distance A to C (mm) |
|---|---|---|---|
| Left foot Standing | | | |
| Left foot Sitting | | | |

# To calculate foot flexibility

First you need to work out the Arch Height Index (AHI) of the foot for both the standing and sitting measurements. You may prefer to make the Foot flexibility calculation process part of a Maths lesson. The calculations include using division, working to one and two decimal places and finding the modal. Check out the cross-curricular links pdf for an additional maths activity.

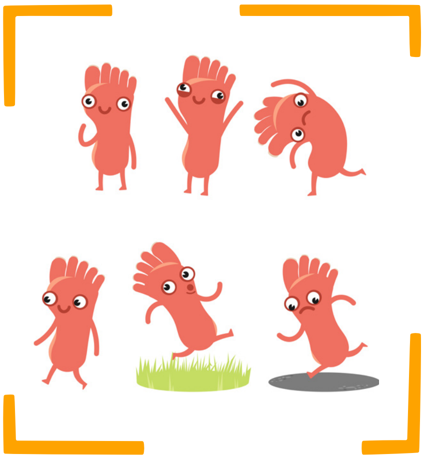
**To calculate AHI:**

- Divide the **height of the foot** by **the distance A to C.**
- Write the AHI of each foot on your sheet. Now you can calculate how flexible the foot is.
- Divide the AHI standing by the AHI sitting.
- Record your result to two decimal places (as for this investigation we are asking pupils to work to two decimal places).
- You should get a figure between 0 and 1.
    - **a)** 1.0 is very inflexible, 0.10 is very flexible.
- If your answer is over 1 please check all your measurements and working out again.

## Don't forget:

The 'how-to' film on our website will really help you to understand how to carry out the investigation bbc.co.uk/guides/zwfp7p3

| | AHI Standing | AHI Sitting | Foot Flexibility (AHI standing divided by AHI sitting) |
|---|---|---|---|
| Left foot | | | |



## Review

Give each child a sticky note and ask them to write down their foot flexibility to two decimal places. Show the children the images of different animals (page 21) with their foot flexibilities. Can they see any patterns?

Explain to the children that our ancestors, who were tree dwelling, would have had a foot flexibility of less than 0.5, similar to most primates today. Ask them to look at the results of the children around them - are our feet more flexible than this (lower number) or less flexible (higher number)?

The expected range is 0.75 to 0.95. If a child's foot flexibility is outside of this range discuss why this might be and allow time for these measurements to be taken again perhaps by another child to see if any of the measurements were not precise.

On the wall or white board, prepare the axes for a bar graph with the numbers spaced up the side to match the size of the sticky notes. Please plot flexibility along the x-axis using the ranges on the next page.

These are the foot flexibility ranges that will be on the class data input page for the Terrific Scientific map.

**<0.700**
**0.700 - 0.749**
**0.750 - 0.799**
**0.800 - 0.849**
**0.850 - 0.899**
**0.900 - 0.949**
**0.950 - 1.000**

**Discuss:**

Talk with the children about the graph.

Stick the sticky notes onto the wall or the whiteboard to make a graph. Ask the children to put their sticky note in the correct place on the bar chart.

Ask the children to talk about the graph.

- What is the range of foot flexibility in our class?
- Where are most of the points?
- Is there a pattern?
- Is there no pattern?
- Is there a pattern but with a few exceptions?

# Activity 2 – Determining terrain

**Ask:**

Which type of surface do you spend most of your time on outside of school?

Show the children the images of the terrain (page 19 and 20.) Ask them to talk to their partner about these surfaces.

- What are these surfaces?
- What do you do on these types of surfaces?
- What is it like walking on these surfaces?
- How can we group these surfaces?

Establish that some surfaces are natural and some are man-made. It is generally easier to walk on the man-made surfaces, as these are usually more even.

Which type of surface do you spend most of your time on outside of school?

**Think about:**

- When you are walking from one place to another e.g. to school and back, or to a friend's houses and back home.
- The surface you play on during break and lunchtime.
- The activities you do in your spare time.

As a class decide whether they generally spend more time on natural or man-made surfaces.

Please write this on the pupil worksheet in the space provided.

This data will be included in the collection for the University of Kent scientists.

BBC TERRIFIC SCIENTIFIC

# The map

**Remember:**

Submit your class's data to our Terrific Scientific map bbc.co.uk/terrificscientific/map

**Watch:**

To see how to submit your data to our map. Watch this short film here: bbc.co.uk/guides/zqwhqhv

Now please use your unique link to the BBC Terrific Scientific Map (this link was emailed to you when you registered) and enter the information for your class.

The two pieces of data which you need to enter into the BBC map page:

1. The class's modal foot flexibility.

2. The terrain type most of the class usually walk/play on.

Now please use your unique link to the BBC map page and enter this information for your class.

Once you have submitted your class results to the map, you will also need to send them to our partner scientists at the University of Kent using this link:

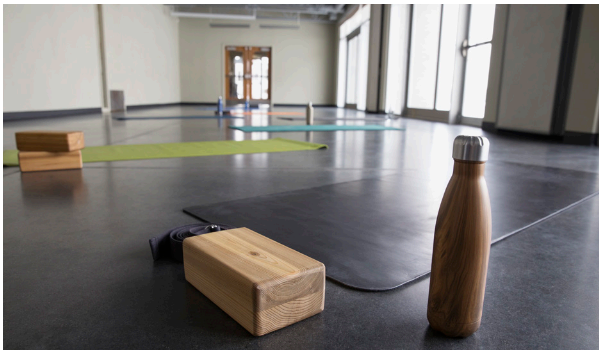
http://www.tssurvey.co.uk

Visit the map page regularly to see how your data compares to other schools around the UK. Remember to click on the Feet tab. bbc.co.uk/terrificscientific/map

# Examples of the terrain could be:


Concrete playground

Field



Gym floor

Astro turf

Pavement

Cobbled street

Country path

Woodland

Hillside

Beach (stony or sandy)

**Discuss:**

How has evolution adapted the animals' feet to suit their environment?

**Our feet are adapted so that we can stand up and walk around. Many animals have feet that are adapted to suit the way that they move or their habitat. Ask the children to search the internet for pictures of the animals' feet outlined below. Discuss the animals' feet and how they may have adapted over time.**

- **Owl** - the feet can bend around branches, the sharp claws help it catch and hold prey.
- **Duck** - the webbed feet aid with swimming.
- **Otter** - the webbed feet help with swimming.
- **Polar bear** - they are furry underneath to prevent the bear slipping on ice, the claws help to catch prey and also dig in the snow to prevent slipping.
- **Horse** - the solid hoof is suited to hard ground.
- **Camel** - the skin between the toes prevents the camel sinking in the sand.

We love hearing about how your students have got on with their terrific scientific investigations. You can contact us at terrific.scientific@bbc.co.uk

# Activity 3 – Measuring foot flexibility of people of different ages

**Tip:**

Support the children to collate this data to produce a scatter graph.

The children can use the same procedure that they have practiced during Activity 1 to collect data about the foot flexibility of people of different ages. This could be carried out during school time using children in different year groups or at home using friends and family.

Support the children to collate this data to produce a scatter graph. This can be easily done using a spreadsheet package to collect the data and then using the graph function to produce the graph. Alternatively, if the children are able to plot points they can do this by hand.

- Are there any patterns in the data?
- Does foot flexibility increase or decrease with age?

## Activity 4 – Looking for patterns in feet

**Discuss:**

Does the size of your foot affect foot flexibility?

During the investigation, the children took measurements of their feet and compared these to their partner's. Their observations can be used to suggest further questions for investigation.

**Example:**

- Observation: I think people with longer feet have narrower feet.
- Question: Do people with longer feet have narrower feet?

The following question frame can be useful for making your own hypothesis:

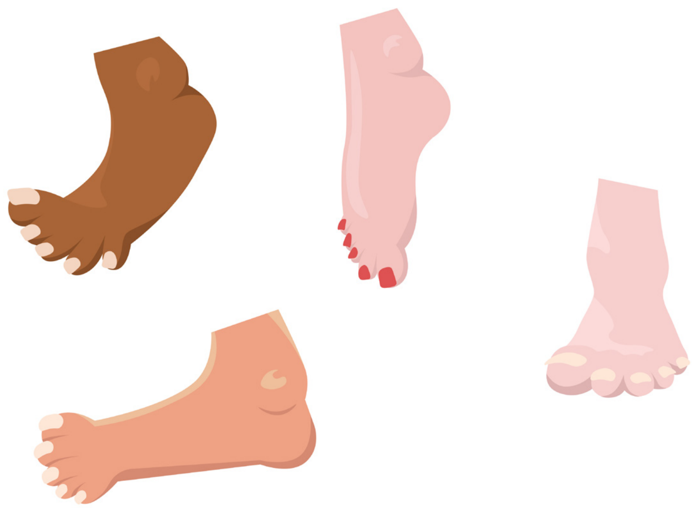
- Do people with____________ have ____________?

When the children have come up with a question, they measure as many people as possible to gather sufficient evidence to support or refute their idea. Plotting their results on a graph will enable them to notice if any patterns in the data are present.

**Related links:**

Find out more about Terrific Scientific and our other investigations on

bbc.co.uk/terrificscientific



# Glossary

| | |
|---|---|
| **Adaptation** | A special feature that helps an animal or plant survive. It can be either a physical trait or a behaviour. |
| **Adapted** | Being suited to a particular habitat or way of life. |
| **Arch Height Index** | A measurement that describes foot shape and structure. |
| **Blubber** | A thick layer of fat under the skin that helps to keep animals warm. |
| **Condensation** | The process when a gas changes into a liquid when temperature is lowered to a certain point. |
| **Dimensions** | Measurements of length, width and depth that describe the shape of something. |
| **Environment** | The physical surroundings of an object or living thing. |
| **Flexible** | Something that bends easily. |
| **Habitat** | The natural home or environment of an animal, plant, or other organism. |
| **Hypothesis** | An idea that describes what you think will happen in a situation that you can test with an experiment. |
| **Inflexible** | The opposite of flexible, something that is doesn't bend easily. |
| **Modal** | A type of average, the value that appears the most. |
| **Nutrient** | A substance in food that helps things to live and grow |
| **Parallel** | Two lines (or objects) that are side by side, going in the same direction and that are always the same distance apart. |
| **Primate** | A group of mammals that includes monkeys, apes and humans. |
| **Organism** | Any living thing such as a plant, animal or bacteria. |

BBC Terrific Scientific

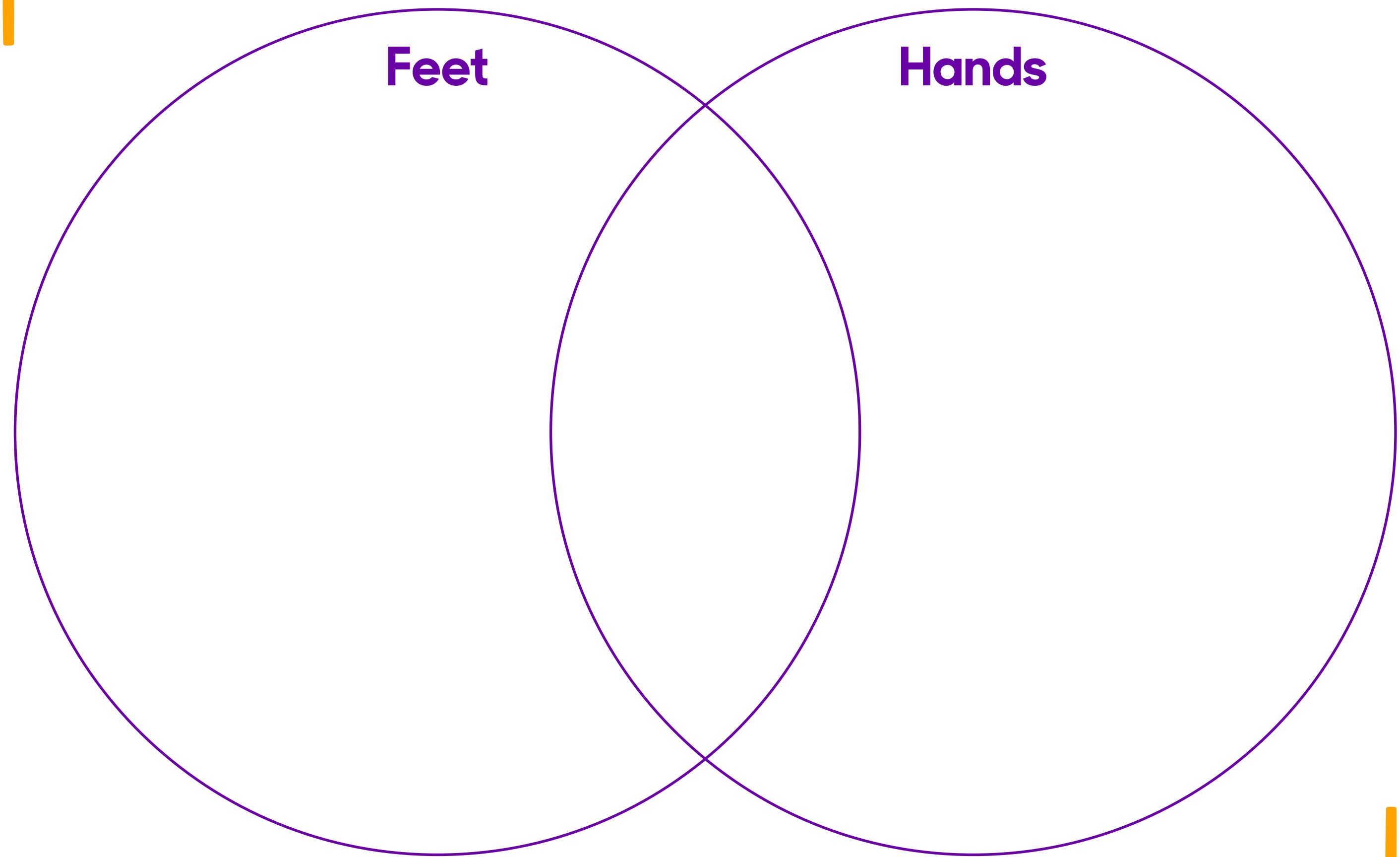
# Feet
# Student Worksheet

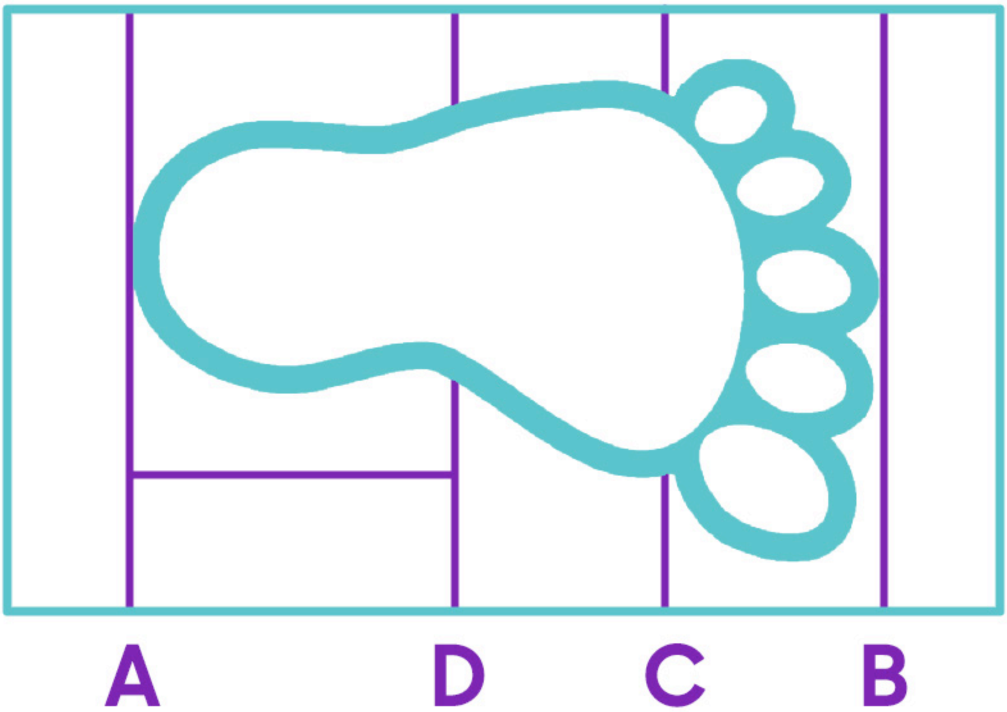
# Compare and contrast

| Only hands |
|---|
| |

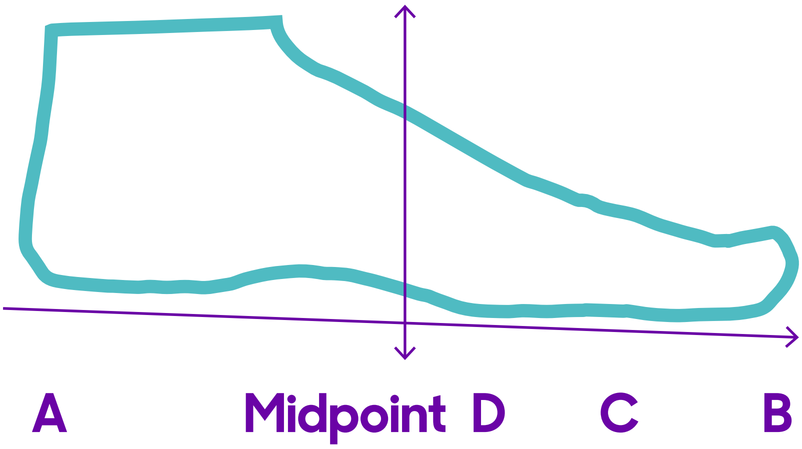
| Only feet |
|---|
| |

| Both hands and feet |
|---|
| |


Feet
Hands




A to B: mm




Height measured at midpoint D = mm

Midpoint (D) A to B ÷ 2 = mm

A to C = mm

| Please write the type of surface you mostly walk on here | Distance A to B in mm | Height of foot in mm | Distance A to C in mm | Arch Height Index (AHI) which is Height divided A to C in mm |
|---|---|---|---|---|
| Left foot standing Student 1 | | | | |
| Left foot sitting Student 1 | | | | |
| Left foot standing Student 2 | | | | |
| Left foot sitting Student 2 | | | | |

Distance from bottom of ruler to 0 cm mark = __________mm

| | Arch Height Index (AHI) standing | Arch Height Index (AHI) sitting | Foot flexibility AHI standing ÷ AHI Sitting |
|---|---|---|---|
| Left foot Student 1 | | | |
| Left foot Student 2 | | | |

## The type of surface I spend most of my time on is.

-----------------------------------------------------------

## Appendix 2

1. What is the postcode of your school?

2. Are answering this survey about yourself or somebody else? Or are you a teacher submitting the overall results from your class?

3. What was the distance in mm from A to B of your foot when you were standing up?

4. What was the height in mm of your foot when you were standing up?

5. What was the distance in mm from A to C of your foot when you were standing up?

6. What was the distance in mm from A to B of your foot when you were sitting down?

7. What was the height in mm of your foot when you were sitting down?

8. What was the distance in mm from A to C of your foot when you were sitting down?

9. What did you calculate your arch height index to be when you were standing up?

10. What did you calculate your arch height index to be when you were sitting down?

11. What did you calculate your foot flexibility to be?

12. Which type of surface do you think that you spend most of your time on outside of school?

13. What is your sex?

14. How old are you?

15. Have you ever broken a bone in your foot or leg?

16. In the last 7 days, during your PE classes, how often were you very active (playing hard, running, jumping, throwing)?

17. In the last 7 days, what did you normally do at break and lunch time (besides eating lunch)?

18. In the last 7 days, on how many days after school, did you do sports, dance, or play games in which you were very active?

19. Where do you mainly do sport, dance, or play games in which you are active after school?

20. Last weekend, how many times did you do sports, dance, or play games in which you were very active?

21. Where do you mainly do sport, dance, or play games in which you are active at the weekend?

22. Would you say that the last 7 days was a normal week of physical activity for you?

23. What was the distance in mm from A to B of the foot you measured when they were standing up?

24. What was the height in mm of the foot you measured when they were standing up?

25. What was the distance in mm from A to C of the foot you measured when they were standing up?

26. What was the distance in mm from A to B of the foot you measured when they were sitting down?

27. What was the height in mm of the foot you measured when they were sitting down?

28. What was the distance in mm from A to C of the foot you measured when they were sitting down?

29. What did you calculate the arch height index to be when standing up?

30. What did you calculate the arch height index to be when sitting down?

31. What did you calculate the foot flexibility to be?

32. Which type of surface does the person whose foot you measured think that they spent most of their time walking on?

33. What is the sex of the person you measured?

34. How old is the person you measured?

35. Has the person you measured ever broken a bone in your foot or leg?

36. What was the most common foot flexibility range found by your class?

37. What sort of ground do the majority of pupils in your class play on outside of school?

Appendix 3

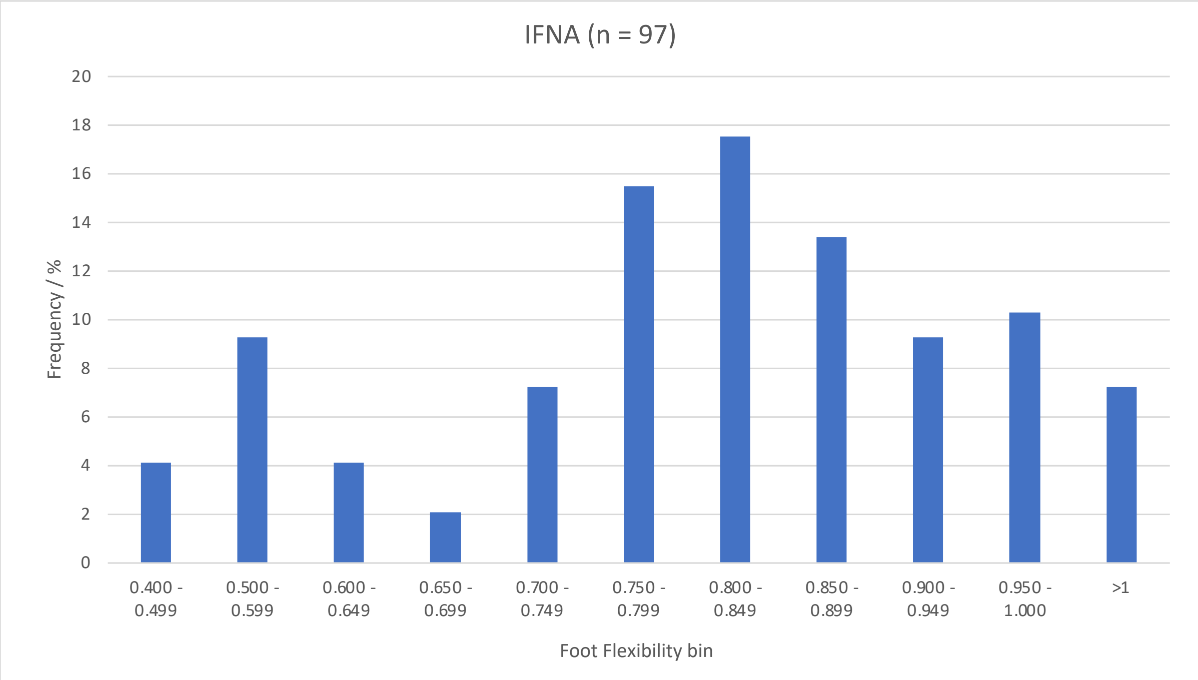



*Figure 1: Frequency percentage of Foot Flexibilities of the Individual dataset for the researcher's classification of Natural terrain After application of the Error CC.*

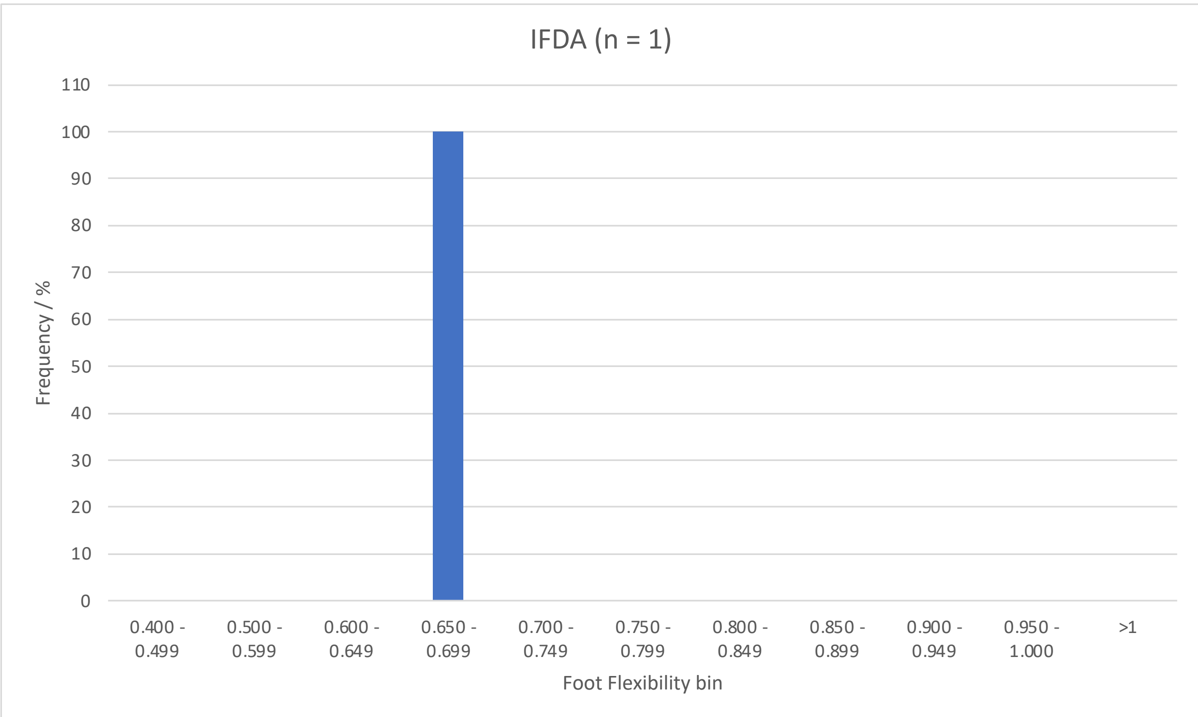



*Figure 2: Frequency percentage of Foot Flexibilities of the Individual dataset for the researcher's classification of Developed terrain After application of the Error CC.*

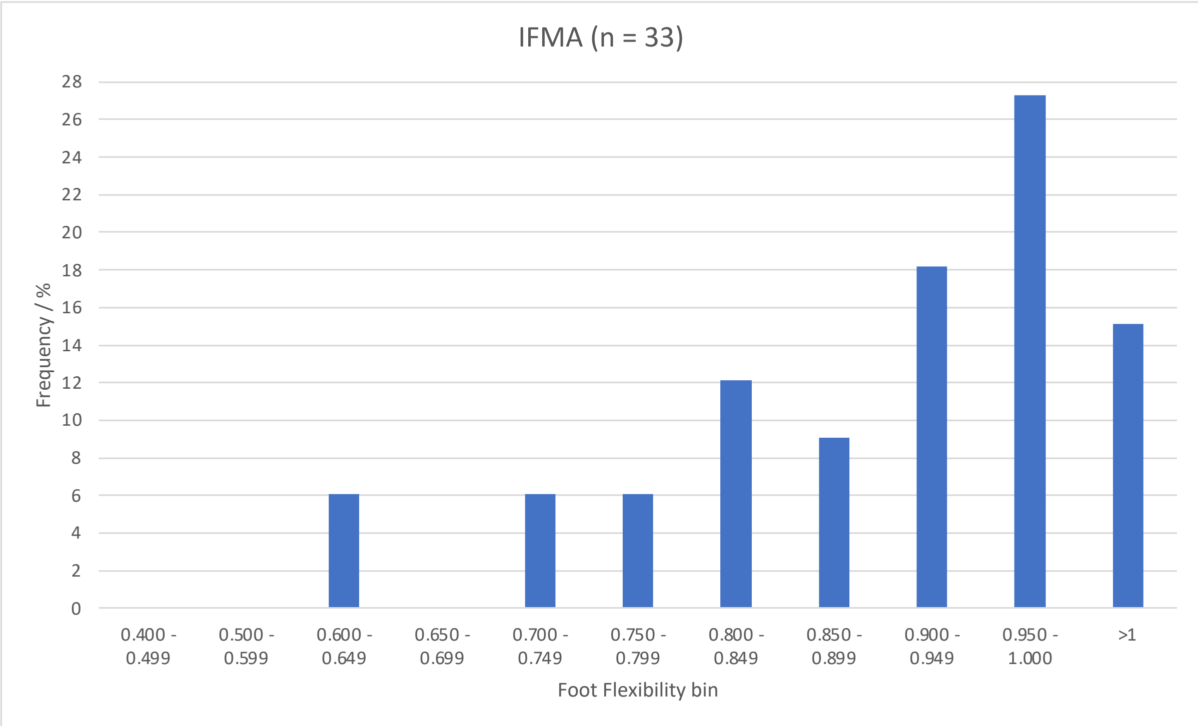



*Figure 3: Frequency percentage of Foot Flexibilities of the Individual dataset for the researcher's classification of Mixed terrain After application of the Error CC.*

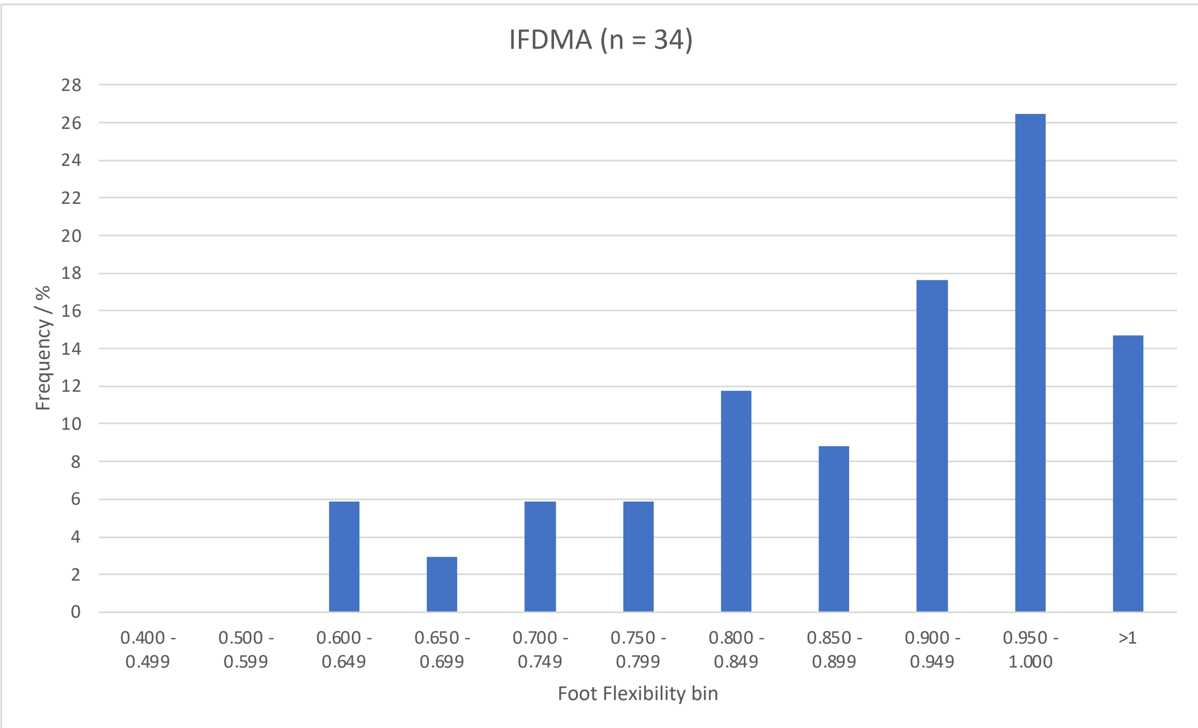



*Figure 4: Frequency percentage of Foot Flexibilities of the Individual dataset for the researcher's classification of Developed + Mixed terrain After application of the Error CC.*

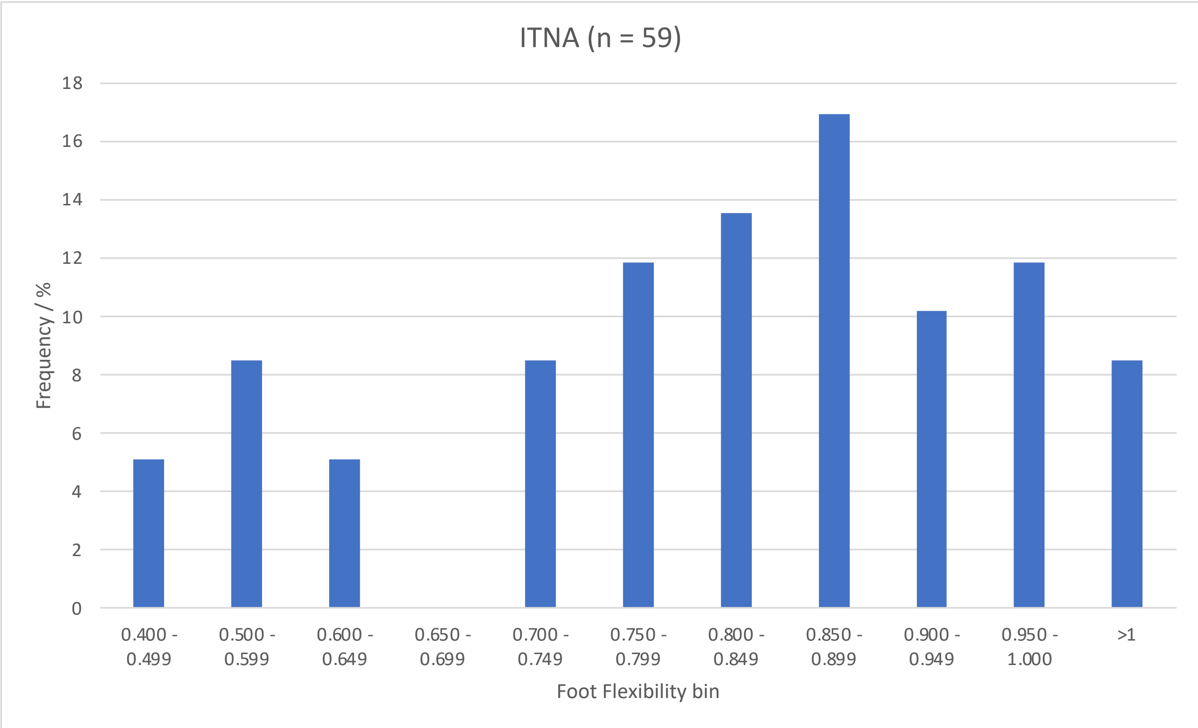



*Figure 5: Frequency percentage of Foot Flexibilities of the Individual dataset for the participants' classification of Natural terrain After application of the Error CC.*

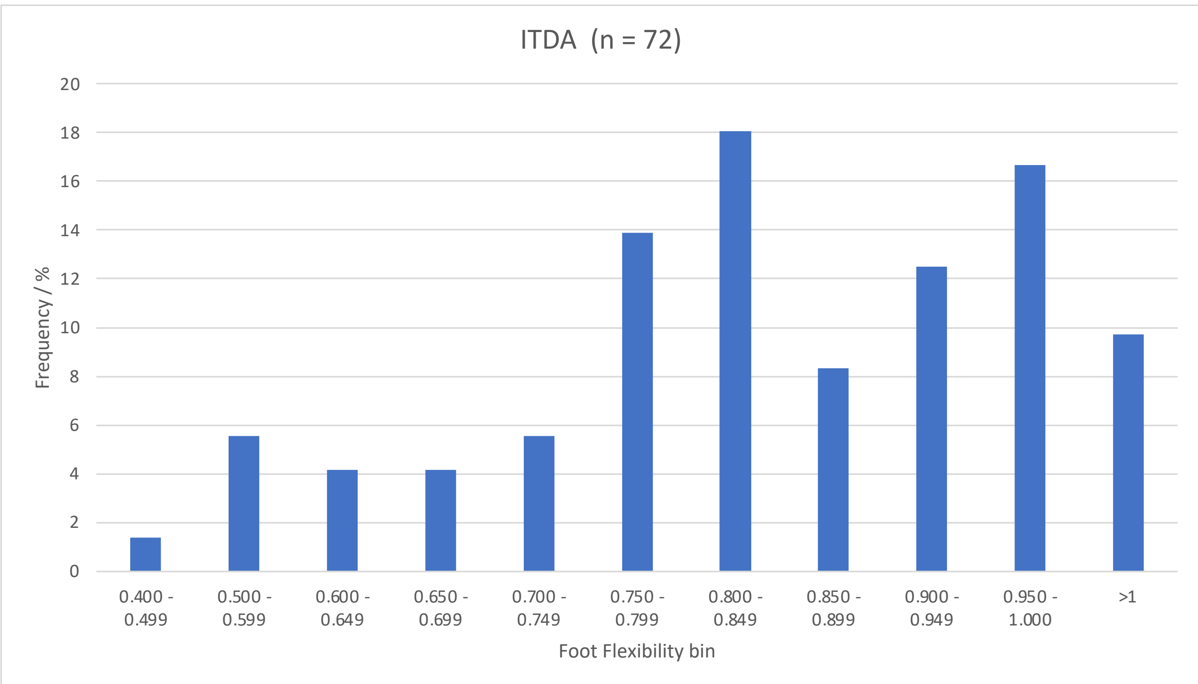



*Figure 6: Frequency percentage of Foot Flexibilities of the Individual dataset for the participants' classification of Developed terrain After application of the Error CC.*

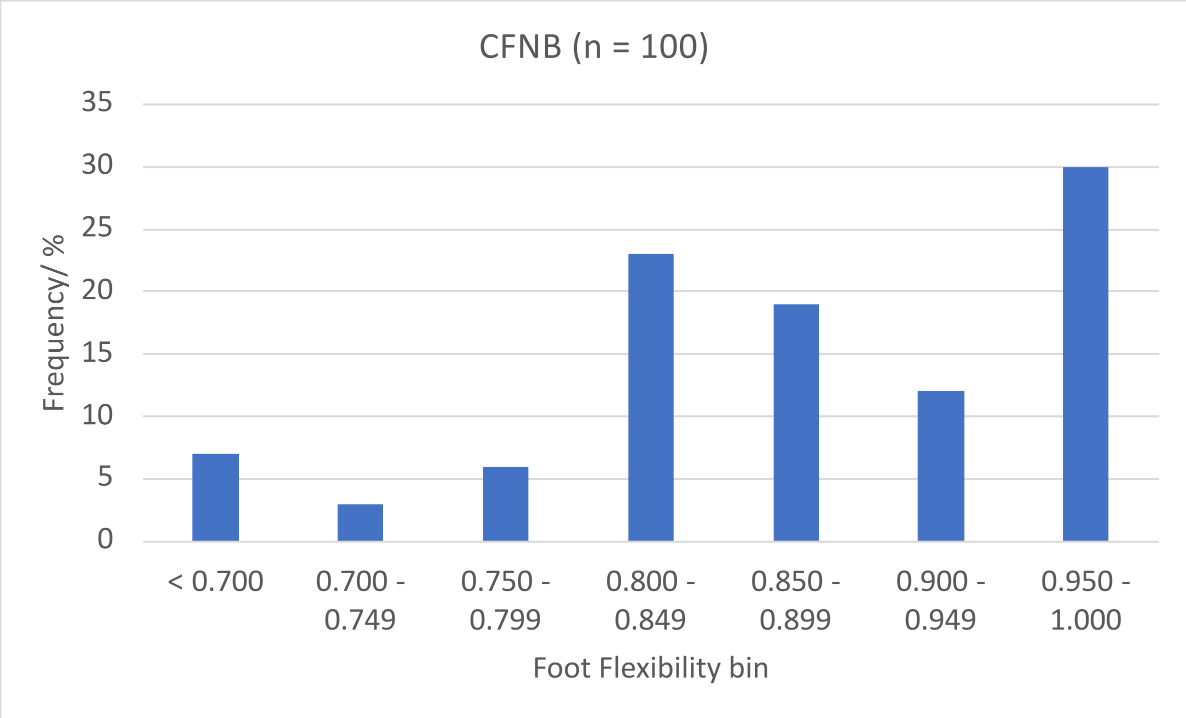



*Figure 7: Frequency percentage of Foot Flexibilities of the Class dataset for the researcher's classification of Natural terrain Before application of the Error CC.*

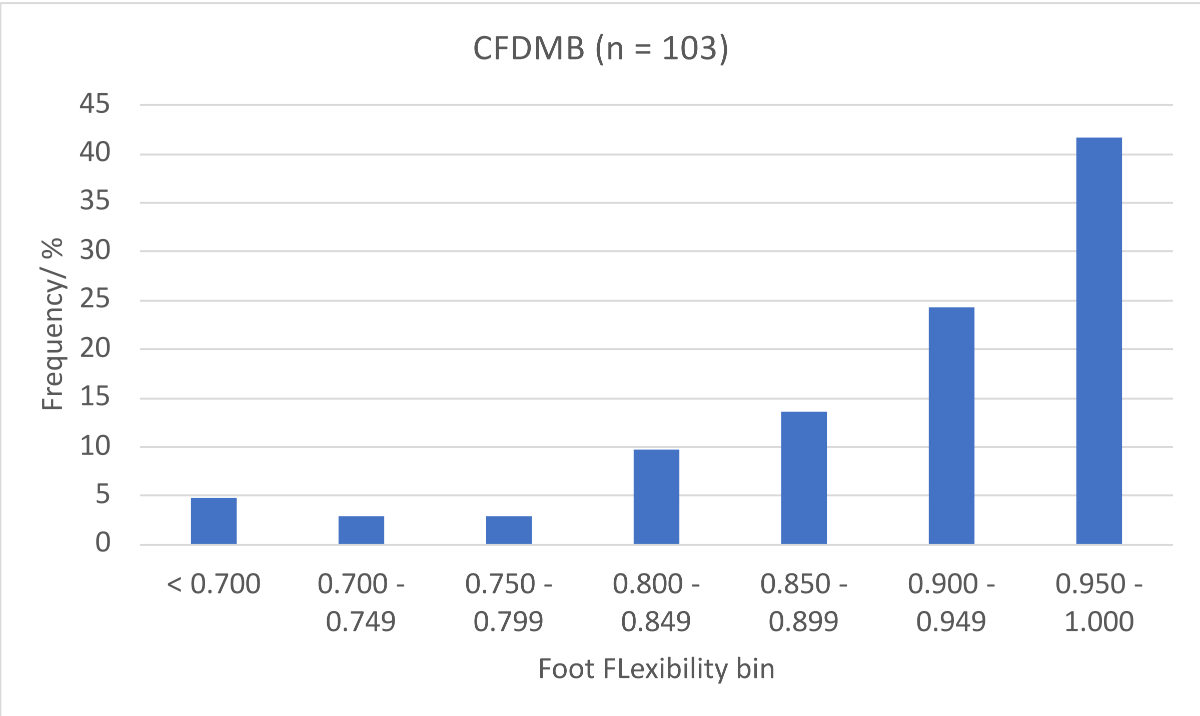



*Figure 8: Frequency percentage of Foot Flexibilities of the Class dataset for the researcher's classification of Developed + Mixed terrain Before application of the Error CC.*

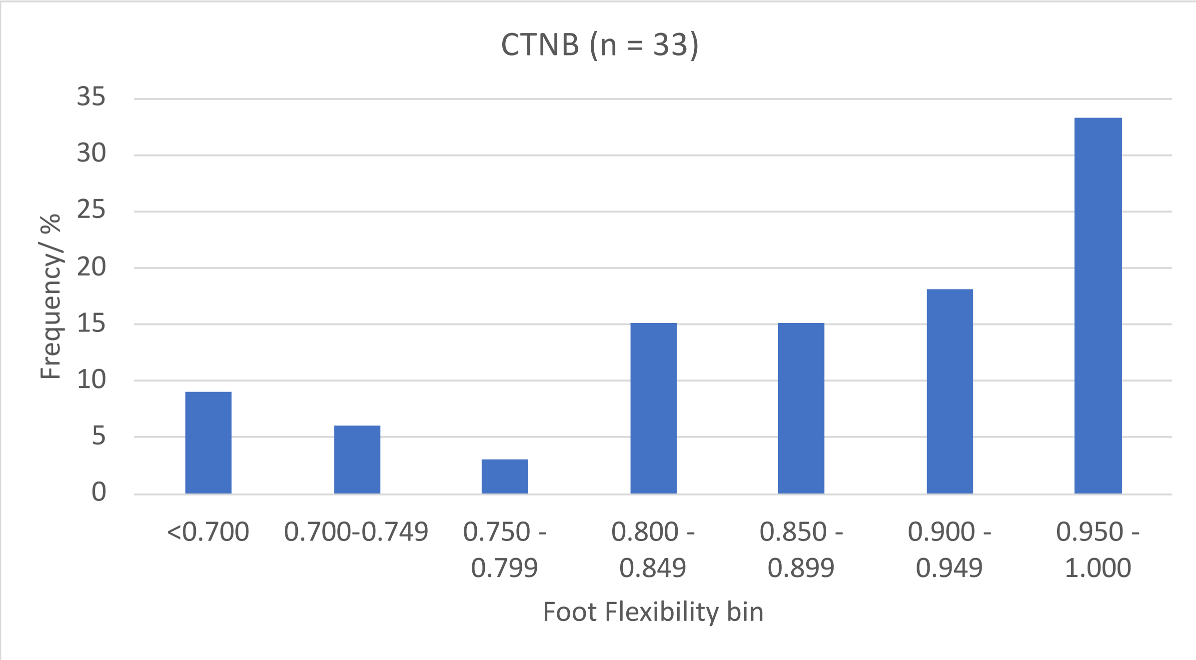



*Figure 9: Frequency percentage of Foot Flexibilities of the Class dataset for the participants' classification of Natural terrain Before application of the Error CC.*

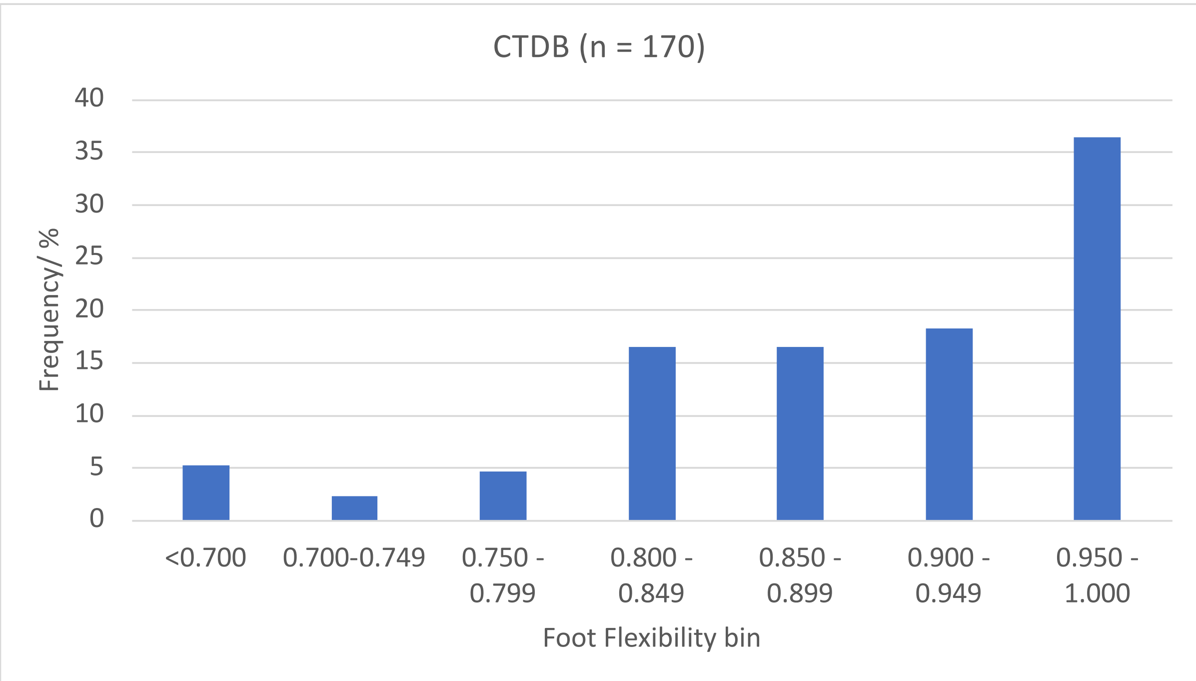



*Figure 10: Frequency percentage of Foot Flexibilities of the Class dataset for the participants' classification of Developed terrain Before application of the Error CC.*

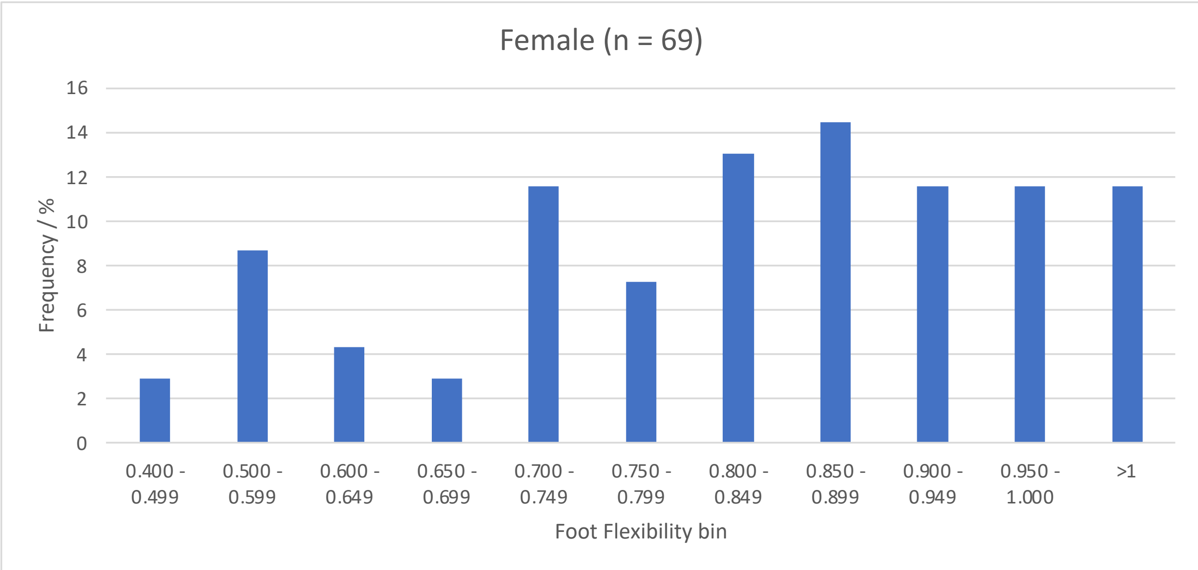



*Figure 11: Frequency percentage of Foot Flexibilities for female participants of the Individual dataset.*

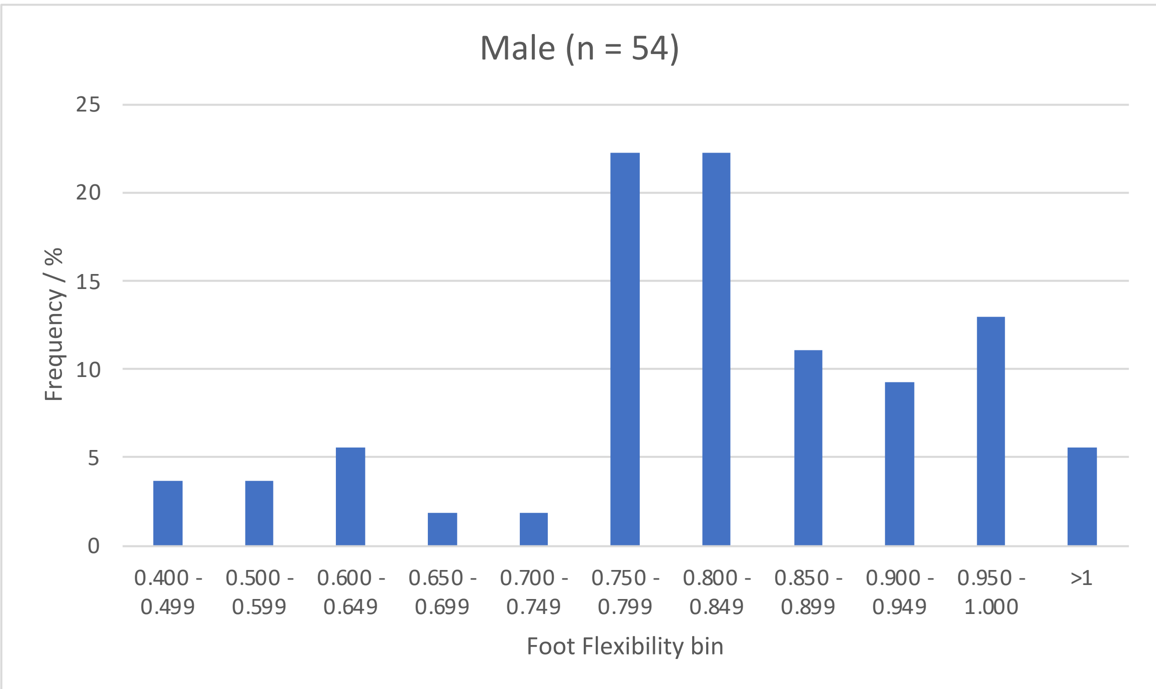



*Figure 12: Frequency percentage of Foot Flexibilities for male participants of the Individual dataset.*

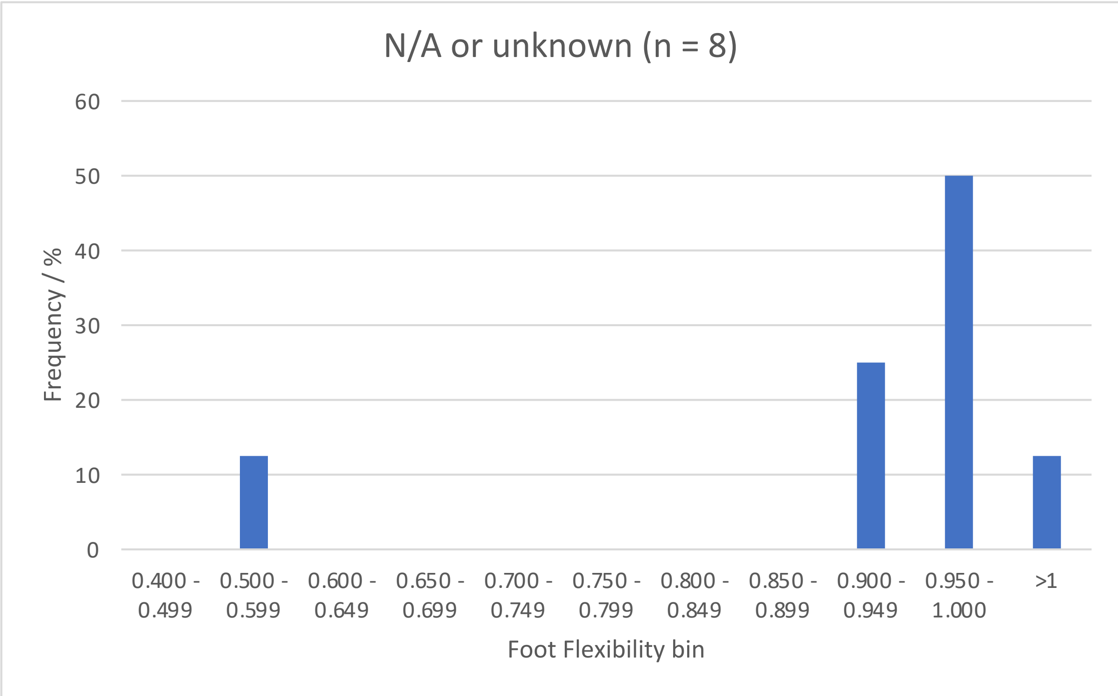



*Figure 13: Frequency percentage of Foot Flexibilities for participants whose gender is unknown or not applicable of the Individual dataset.*

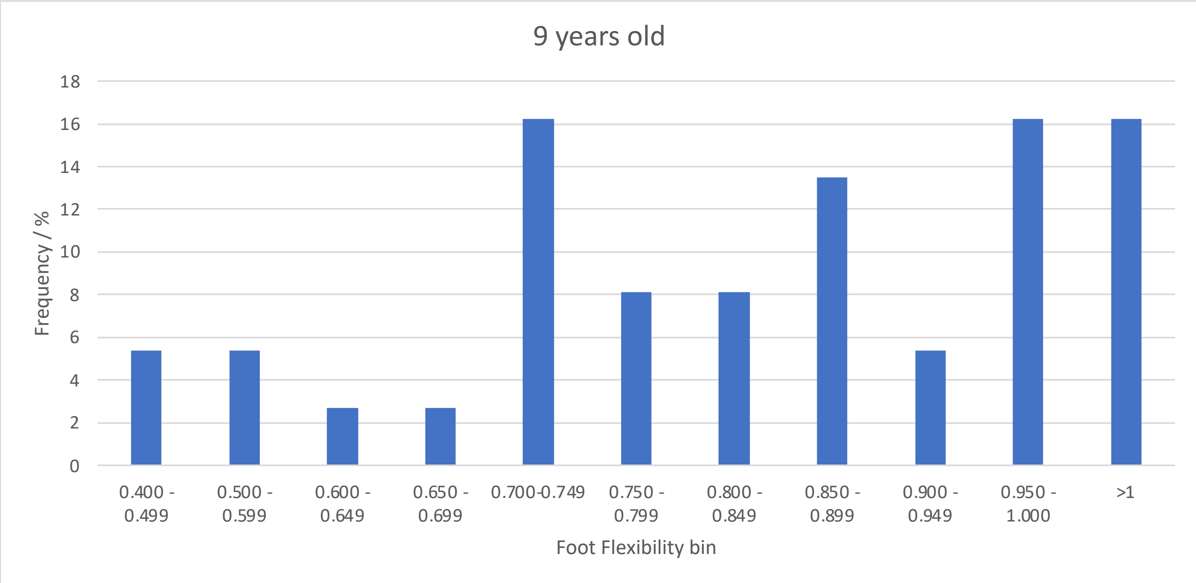



*Figure 14: Frequency percentage of Foot Flexibilities for 9 year old participants of the Individual dataset.*

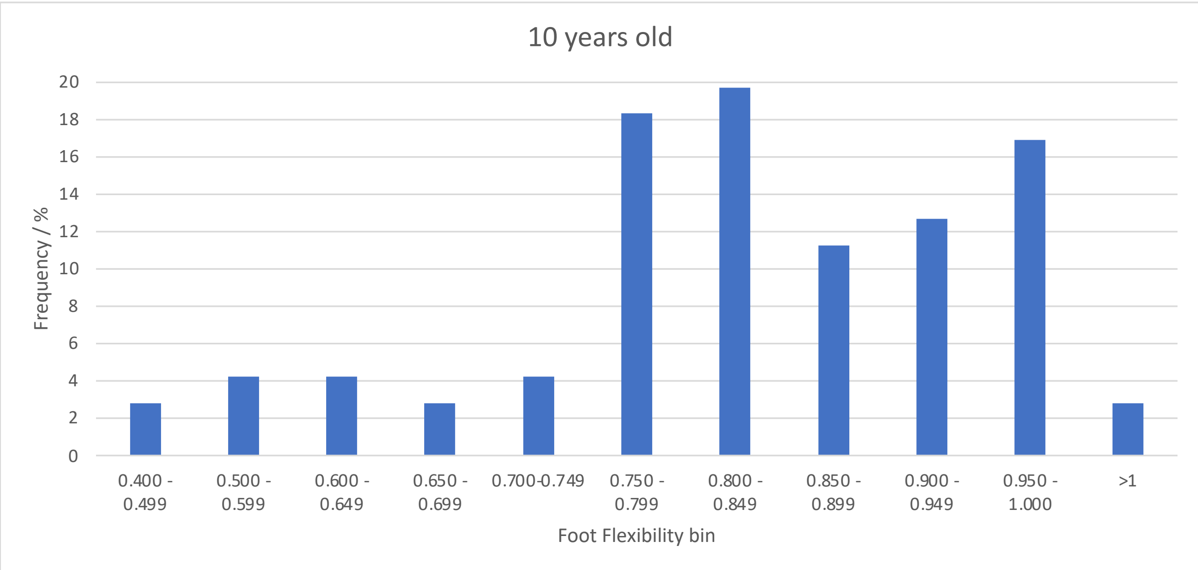



*Figure 15: Frequency percentage of Foot Flexibilities for 10 year old participants of the Individual dataset.*

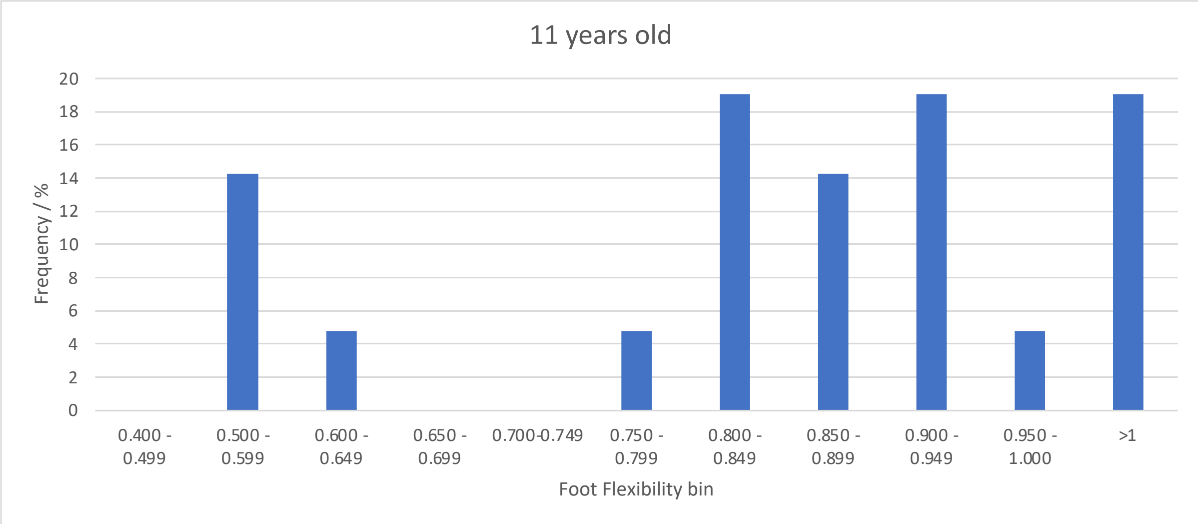


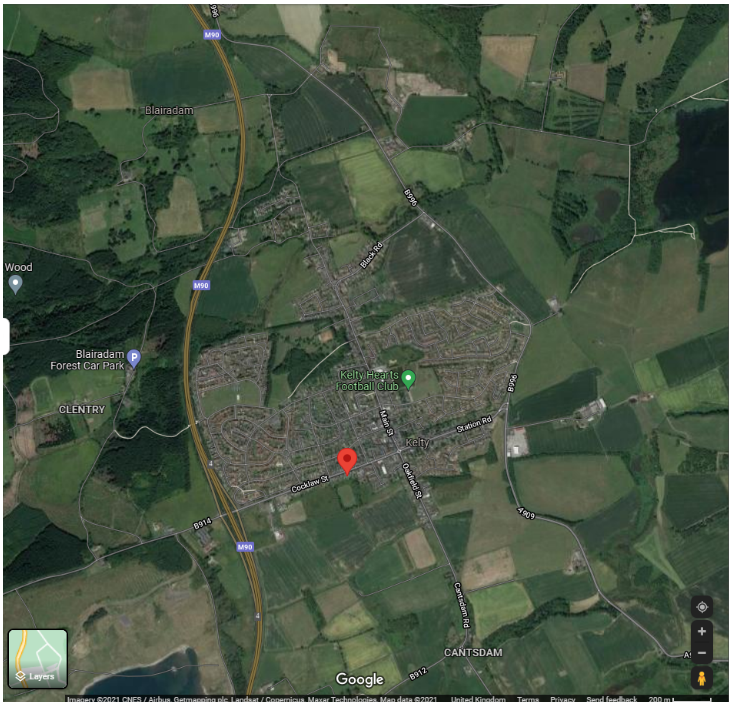

*Figure 16: Frequency percentage of Foot Flexibilities for 11 year old participants of the Individual dataset.*

# Appendix 4

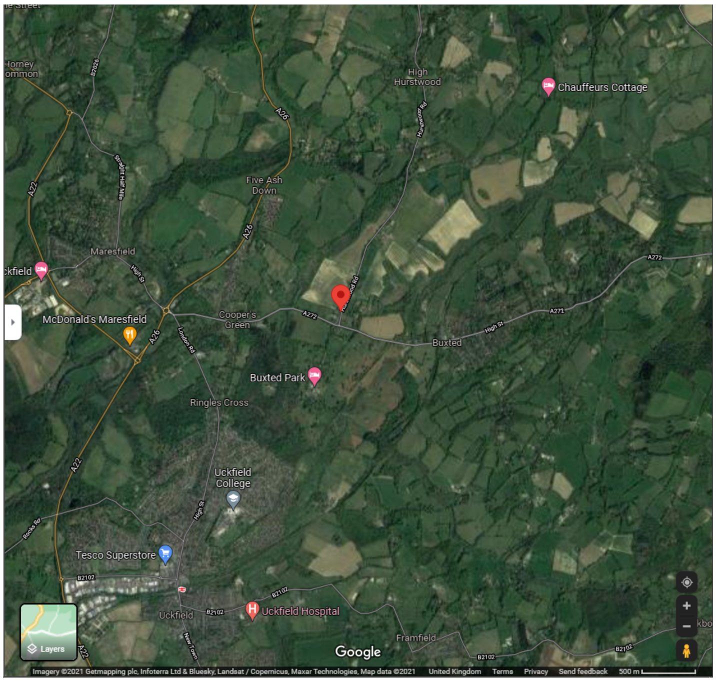
Overview of avarage AHI and FF values calculated by the researcher and the participants separated by school as part of the Preliminary Dataset.

| Measurements performed by: | School A | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Left feet | | | | Right feet | | | |
| | AHI-sitting | AHI-standing | FF | n | AHI-sitting | AHI-standing | FF | n |
| Researcher | 0.386 | 0.326 | 0.847 | 17 | 0.380 | 0.330 | 0.870 | 16 |
| Participants | 0.399 | 0.359 | 0.910 | 26 | 0.386 | 0.370 | 0.969 | 25 |
| | School B | | | | | | | |
| | Left feet | | | | Right feet | | | |
| | AHI-sitting | AHI-standing | FF | n | AHI-sitting | AHI-standing | FF | n |
| Researcher | 0.350 | 0.300 | 0.860 | 8 | 0.377 | 0.314 | 0.834 | 11 |
| Participants | 0.338 | 0.285 | 0.845 | 6 | 0.367 | 0.316 | 0.712 | 10 |
| | School C | | | | | | | |
| | Left feet | | | | Right feet | | | |
| | AHI-sitting | AHI-standing | FF | n | AHI-sitting | AHI-standing | FF | n |
| Researcher | 0.372 | 0.322 | 0.871 | 13 | 0.382 | 0.328 | 0.863 | 25 |
| Participants | 0.411 | 0.301 | 0.737 | 3 | 0.433 | 0.357 | 0.878 | 4 |

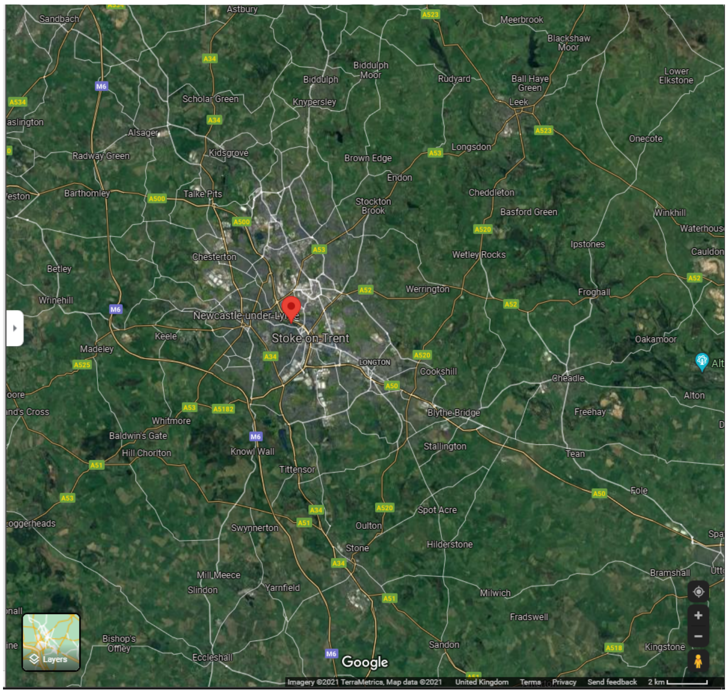
# Appendix 5



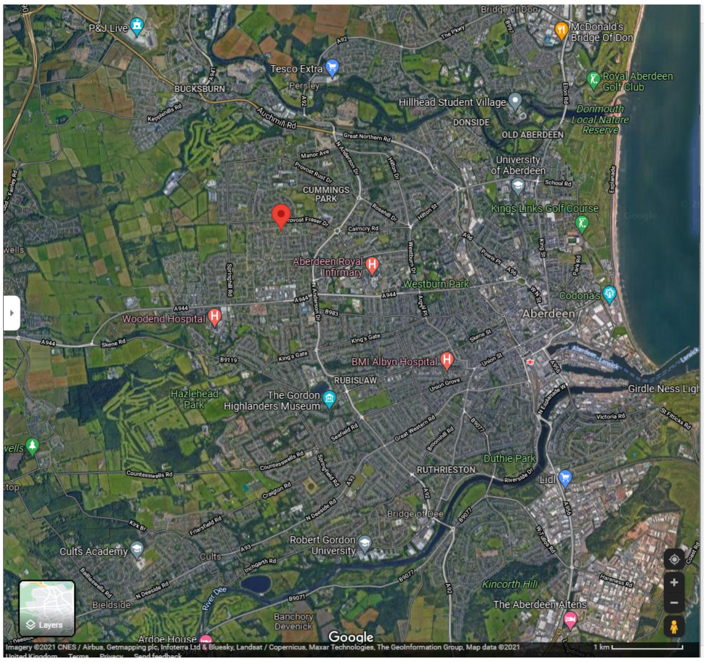
Natural terrain: relatively small urban area, lots of fields around.



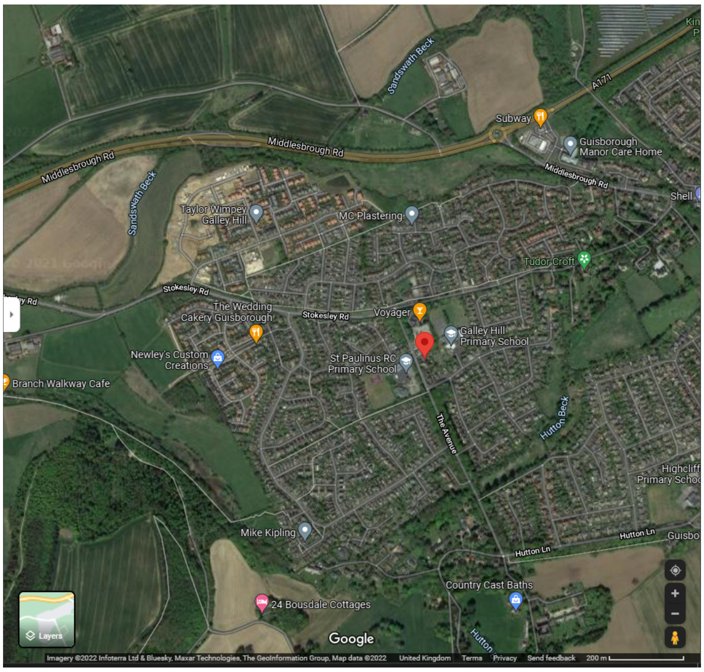
Natural terrain: much more Natural terrain than Developed.



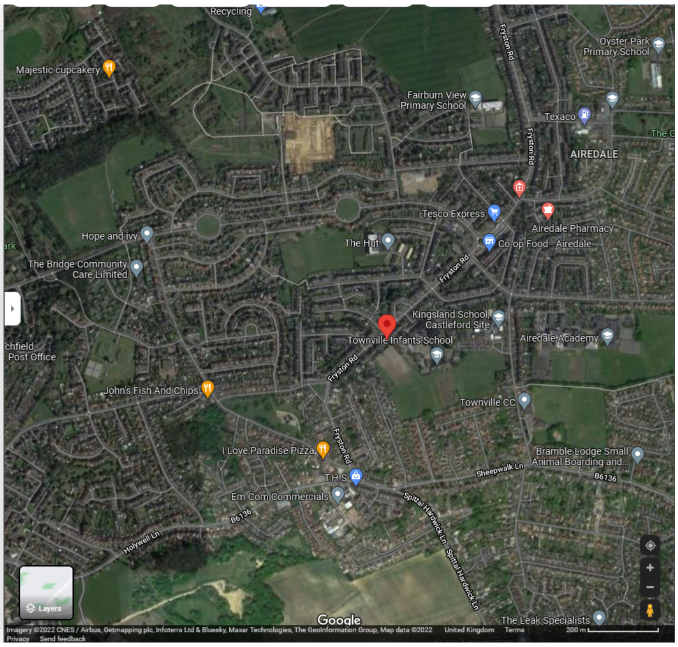
Developed: big city.



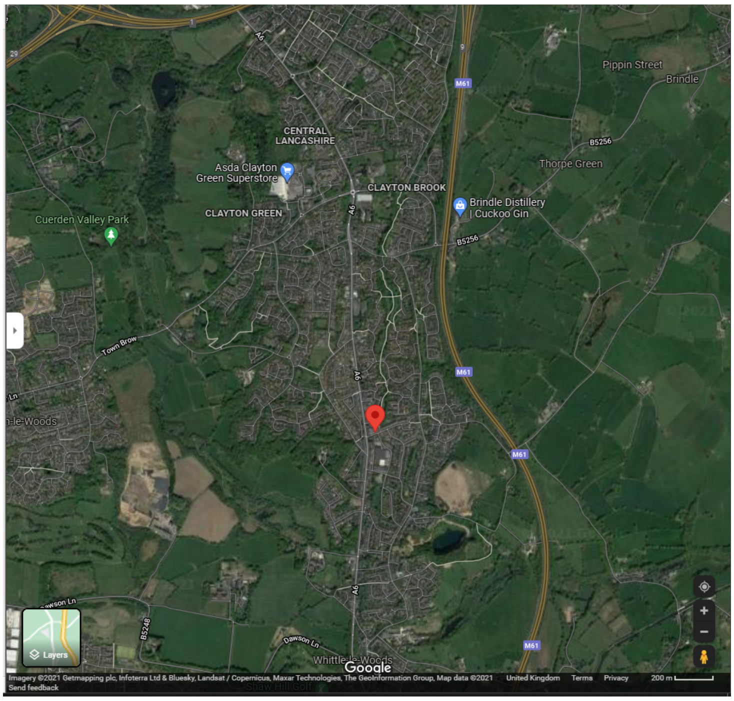
Developed: big city, although next to fields.



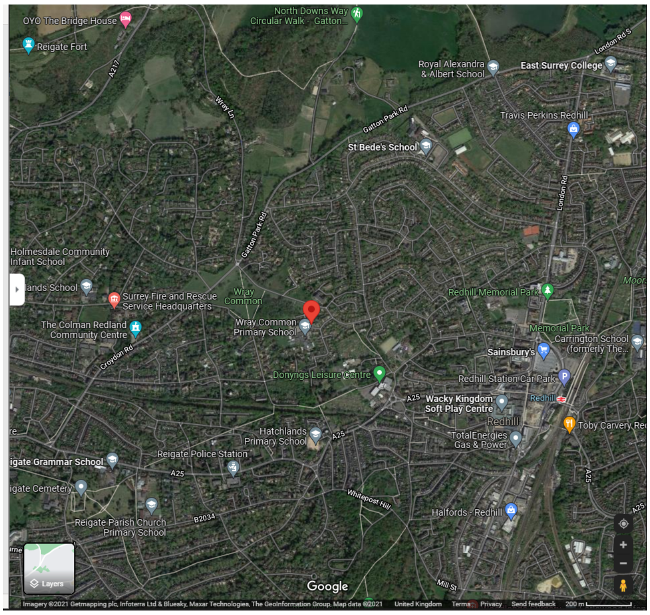
Mixed: smaller area separated from bigger town. Lots of gardens.



Mixed: big town. Quite a bit of green incorporated.



Mixed: towards bigger side of town, surrounded by fields and lots of green in town.



Mixed: bigger town, surrounded by fields. Green incorporated in town.

# Appendix 6

The section column defines the area of analysis which corresponds with the section; the description column focusses in on the area within the section analysed; the variables column specifies the two sub-populations compared. The P-values are presented under their respective test names. Abbreviations: Right feet (R), Left feet (L), Individual (I), Class (C), Researcher's classification (F), Participants' classification (T), Natural (N), Developed (D), Mixed (M), Before Error CC (B), After Error CC (A).
Yellow fields indicate statistically significant P-values; green fields indicate relevant statistically insignificant P-values referred to in text; white numerical fields indicate insignificant P-value not referred to in text.
N/A: no calculation was performed where the test and comparison were not compatible, or for one-sided tests deemed unnecessary.
(u): bin range included from 0.400 – 0.499 to 1.001 – 1.099; (l): bin range included from 0.400 – 0.499 to 0.950 – 1.000
(greater): one-sided test using the alternative hypothesis that the first variable value is greater than the second variable value, (less): one-sided test using the alternative hypothesis that the first variable value is less than the second variable value.

| **Section** | **Description** | **Variables** | **Paired t-test: only feet measured by both parties** | **One sided paired T-test (less)** |
|---|---|---|---|---|
| 2.3.2. Preliminary Before Error CC | Researcher - Participants | Researcher - Participants B | 0.03919 | 0.0196 |
| | Right - Left Before Error CC | Researcher R - Researcher L | 0.8007 | N/A |
| | | Participants RB - PLB (Pupil R/L) | 0.1508 | N/A |
| | Researcher - Participants Before Error CC | Researcher R - Participants RB | 0.03642 | 0.01821 |
| | | Researcher L - Participants LB | 0.5537 | 0.2768 |
| 2.3.2. Preliminary After Error CC | Researcher - Participants | Researcher - Participants A | 0.9581 | 0.4791 |
| | Researcher - Participants After Error CC | Researcher R - Participants RA | 0.3582 | 0.1791 |
| | | Researcher L - Participants LA | 0.2477 | 0.8762 |

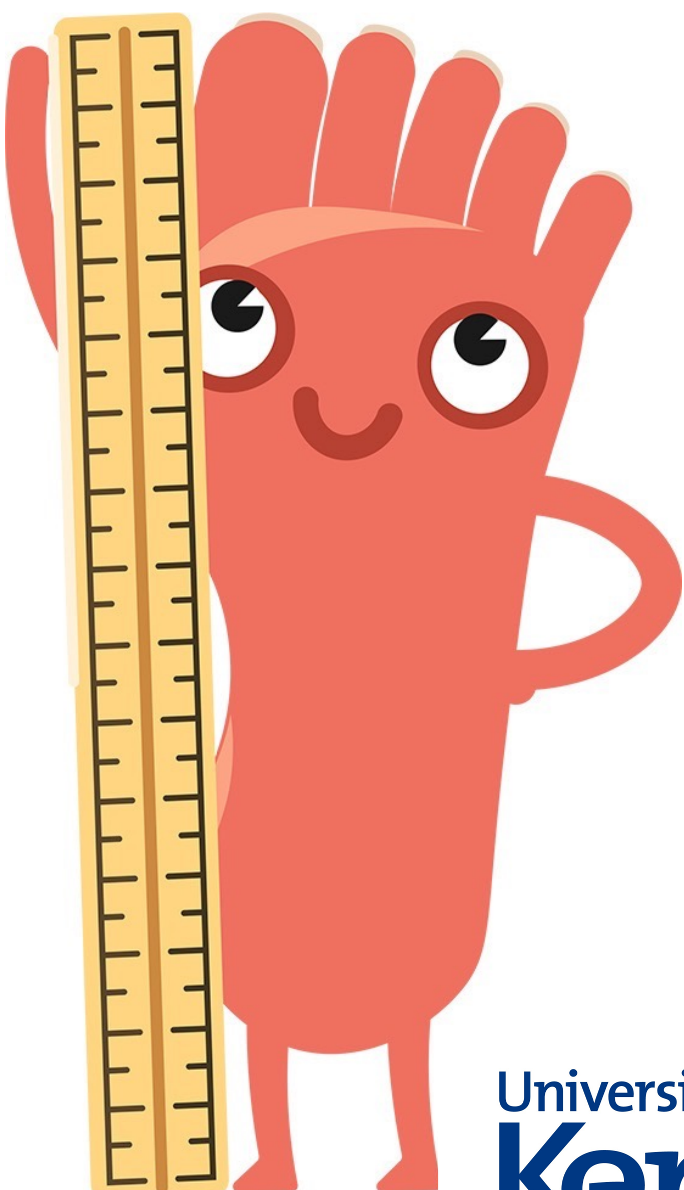
| | | | P-value paired Wilcoxon | P-value one-sided paired Wilcoxon (greater) | |
|---|---|---|---|---|---|
| 2.3.3. AHI BBC Dataset | Sitting - Standing | n/a | 1.43E-10 | N/A | |
| 2.3.4. Error CC | Before - After Error CC | $IB_{(u)}$ - $IA_{(u)}$ | 0.008806 | <2.2e-16 | |
| | | | **P-value Wilcoxon** | **P-value Chi-Squared** | **P-value one-sided Wilcoxon (less)** |
| 2.3.5. Individual - Class | Individual - Class | IB(I) - CB | N/A | 0.001523 | N/A |
| | | IA(I) - CB | N/A | 2.62E-06 | N/A |
| 2.3.7. Classification of Terrain | I+C combined before Error CC | FNB - TNB | N/A | 0.8457 | N/A |
| | | FDB - TDB | N/A | 0.3555 | N/A |
| | | FNB - TDB | N/A | 0.129 | N/A |
| | | FDB - TNB | N/A | 0.3773 | N/A |
| | | FNMB - TNB | N/A | 0.6894 | N/A |
| | | FDMB - TDB | N/A | 0.1704 | N/A |
| | Individual before Error CC | IFNB - ITNB | 0.681 | 0.9223 | N/A |
| | | IFNMB - ITNB | 0.6349 | 0.9303 | N/A |
| | | IFDMB - ITDB | 0.07847 | 0.9303 | N/A |
| | Class before Error CC | CFNB - CTNB | N/A | 0.8215 | N/A |
| | | CFDB - CTDB | N/A | 0.323 | N/A |
| | | CFNMB - CTNB | N/A | 0.8101 | N/A |
| | | CFDMB - CTDB | N/A | 0.5867 | N/A |
| | I+C combined after Error CC | FNA - TNA | N/A | 0.93 | N/A |
| | | FDA - TDA | N/A | 0.5082 | N/A |
| | | FNA - TDA | N/A | 0.2815 | N/A |
| | | FNMA - TNA | N/A | 0.6063 | N/A |
| | | FDMA - TDA | N/A | 0.2682 | N/A |
| | Individual after Error CC | IFNA - ITNA | 0.6038 | 0.9882 | N/A |
| | | IFNMA - ITNA | 0.6166 | 0.9855 | N/A |
| | | IFDMA - ITDA | 0.04767 | 0.7676 | N/A |
| 2.3.6. Terrain, | I+C combined | FNB - FDB | N/A | 0.08805 | N/A |
| | | FNB - FDMB | N/A | 0.0001307 | N/A |

| | | | | | |
|---|---|---|---|---|---|
| Individual + Class combined | Researcher's classification | FNMB - FDB | N/A | 0.132 | N/A |
| | | FNA - FDA | N/A | 0.07672 | N/A |
| | | FNA - FDMA | N/A | 2.49E-05 | N/A |
| | | FNMA - FDA | N/A | 0.2443 | N/A |
| | I+C combined Participants' classification | TNB - TDB | N/A | 0.06319 | N/A |
| | | TNA - TDA | N/A | 0.04792 | N/A |
| 2.3.6. Terrain per classification | Researcher's classification before Error CC | IFNB - IFDMB | 0.006489 | 0.1576 | 0.003245 |
| | | CFNB - CFDB | N/A | 0.1521 | N/A |
| | | CFNMB - CFDB | N/A | 0.1257 | N/A |
| | | CFNB - CFDMB | N/A | 0.02904 | N/A |
| | Researcher's classification after Error CC | IFNA - IFDMA | 0.002038 | 0.124 | 0.001019 |
| | Participants' classification | ITNB - ITDB | 0.5065 | 0.2793 | 0.2533 |
| | | CTNB - CTDB | N/A | 0.8934 | N/A |
| | | ITNA - ITDA | 0.4805 | 0.6308 | 0.2402 |
| 2.3.8. Agreed Terrain | Individual | INB - IDMB | 0.0202 | 0.116 | 0.0101 |
| | | INA - IDMA | 0.00995 | 0.1131 | 0.004975 |
| | Class | CNB - CDB | N/A | 0.9661 | N/A |
| | | CNMB - CDB | N/A | 0.911 | N/A |
| | | CNB - CDMB | N/A | 0.6682 | N/A |
| | Individual + Class combined | NB - DB | N/A | 0.3368 | N/A |
| | | NMB - DB | N/A | 0.3682 | N/A |
| | | NB - DMB | N/A | 0.0016 | N/A |
| | | NA - DA | N/A | 0.2478 | N/A |
| | | NMA - DA | N/A | 0.247 | N/A |
| | | NA - DMA | N/A | 9.84E-05 | N/A |
| 2.3.9. Gender | Female - Male | IA | 0.7004 | 0.1975 | N/A |
| | Male - Unknown | | 0.01921 | 0.1715 | N/A |
| | Female - Unknown | | 0.05922 | 0.2581 | N/A |
| 2.3.9. Age | Nine - Ten | IA | 0.8409 | 0.1019 | N/A |
| | Ten - Eleven | | 0.2374 | 0.1188 | N/A |
| | Nine - Eleven | | 0.5387 | 0.2865 | N/A |

# Volunteers wanted for MSc Thesis

**Purpose of study:**
**To investigate the correlation between terrain being walked on and the morphology of a foot.** We will analyse pressure distribution, surface contact and gait from walking on 2 different terrain types.

## Does where you live affect your foot flexibility?



**Participant requirements:**
- Aged between 18-55 years
- Women shoe sizes between 4.5-6 and 7.5-9.5
- Men shoe sizes between 5.5-6.5 and 8-10
- Able to walk for 15 minutes
- Able to come to the University of Kent Canterbury Campus for 1 hour

**In a 1 hour session we will ask you to:**
- Complete some questionnaires regarding health and physical activity
- Allow us to take measurements of your foot regarding its flexibility
- Allow us to scan your foot to get the arch shape
- Walk outside for approximately 15 minutes with smart insoles in trainers

University of Kent

**Logistics:**
The visit will take place at the University of Kent Canterbury Campus the first week of August 2022. The outside activity of walking on woodland and pavement will not take place during adverse weather conditions.

**To apply:**
Please email Fiep Bargeman (lead researcher): fb228@kent.ac.uk

# Appendix 8

## Participant Information Sheet 06/05/2022 Version 1.1

Chipperfield Building Room 114, University of Kent
Canterbury Campus, Kent, CT2 7PE, UK

# Foot Function Response to Terrain – Research Study

This information sheet will provide you with an insight into the research being performed and details for participants. If you are interested or would like more information, you can contact Fiep Bargeman (fb228@kent.ac.uk) or anyone from the Research team (see details at the end of this form).

## What is the purpose of the research?

The purpose of the research is to investigate the effect of terrain (ground surfaces as woodland or pavement) on the morphology (shaping) of the foot. By using smart insoles, the pressure distribution of the foot, surface contact and gait will be measured. This will help us understand if the foot's morphology (momentarily) changes depending on the terrain and if growing up on a certain terrain will affect the foot's structure in the long term.
The morphology of a foot determines its function and health, which in turn affects the type and level of injuries experienced in the lower extremities. If a correlation between location and foot morphology is determined, specific health services can be designed for people living in different areas, providing personalised foot care.

## Who can take part in this study?

You can choose to take part in this study if you are between the ages of 18 and 55 years and don't have any mobilities issues/ walking impairment (e.g., you are a wheelchair user, you have a cast on one of your feet, you experience pain while walking). You must be able to make your way to the University of Kent Canterbury campus one time between May and June 2022. You must be comfortable walking outside for a few minutes (we will not do the experiment in adverse weather conditions).

## How long am I expected to be part of the study?

The initial assessment, which will take place in the Chipperfield building, is expected to take approximately 30 minutes. You will then be asked to walk outside on the Canterbury campus for approximately 10 minutes. Finally, you will be required to complete some questionnaires (more details below in "what will I be asked to do if I agree to take part?") for the study, which will take approximately 20 minutes.

## Do I have to take part in the study?

Taking part is voluntary. It is up to you whether you want to join the study. If you agree to take part we will ask you to sign a consent form and will give you a copy of this form. However, you are free to withdraw from the study at any time without giving a reason.

## What will I be asked to do if I agree to take part?

The entire assessment is expected to take around 1 hour. You will be asked to meet the research team in Chipperfield Building at the Canterbury campus of University of Kent (CT2 7PE) and to wear/bring your normal footwear (preferably trainers).
You will be asked to complete a General Health Questionnaire, International Physical Activity Questionnaire, Participant Data Sheet and a Consent Form. These questionnaires will provide us with

insight to your usual levels of physical activity and general state of health. A question regarding hormone treatment will be included but is not mandatory to answer.

Then we would take a few measurements of your feet, namely the length and height. This will allow us to classify the foot as a particular type, which is helpful for the data analysis. We will also ask you to stand on a Foot Scan machine so we can visualise the resting surface contact and pressure distribution of your feet. We will also use a 3D scanner to map the shape of your feet.
Lastly, we will fit a smart insole in your normal footwear and ask you to walk on woodland terrain and pavement on the Canterbury campus for a few minutes. We will be able to measure pressure distribution, surface contact and gait for these different terrains and visualise potential differences.

## What are the possible risks of taking part?

You will be asked to walk on a woodland ground, which is associated with uneven surfaces. You will be asked to walk at your normal and preferred pace, which allows you to be comfortable while walking on the woodland. Because the terrain is uneven, there is a small chance that you could trip, but this is unlikely as we will ensure good visibility and remove any major trip hazards. The researcher supervising the session, will have the SafeZone app (provides a direct link to campus security) downloaded on their phone to call for first aider to assist if required.

## What are the possible benefits from taking part?

Taking part in this research study is on a voluntary basis. We are unable to reimburse you for your time and travel. You will have the opportunity to gain insight in to the mechanics of your foot during the study through conversation with the research team.

## Will my taking part be confidential?

Your personal information and data generated form the testing is confidential. At the start of the study, you will be given a participant number, which allows us to collect your data anonymously. Your consent form, which will contain your name and signature, will be kept in a locked cabinet at the University of Kent and is only accessible by the research team.
Your name or any identifying information will not be made public or shared with any third parties.

The consent form is the only form that will contain information that can identify you (e.g. name) and this will be stored securely within the Division of Natural Sciences' premises in accordance with the Data Protection Act 2018 and the University's own data protection procedures. This will be accessible only by the primary research team (Fiep Bargeman, Robert Barker and Lex Mauger). You can access the University of Kent's privacy notice related to research here:

https://cdn-researchkent.pressidium.com/ris-operations/wp-content/uploads/sites/2308/2020/06/GDPR-Privacy-Notice-Research.pdf.

No personal data will be passed on to any third party. The results may be published in scientific journals and/or conferences but all data will be anonymous (i.e. you will be represented only by a code or the results will only present overall group summaries of all data combined). You can receive a copy of your personal results and/or a summary of the overall findings if you wish.

## What will happen to the results of the research?

The anonymised results will be included in a masters thesis and may be kept to support publication. The signed consent forms may be kept up to 12 months, following University policy. The data will be securely destroyed after these 12 months.
The anonymous results may be kept for up to 5 years, following University policy. The data will be securely destroyed after these 5 years.

## Who is organising and funding the study?

The study is supported by the division of Natural Sciences at the University of Kent.

## Who has reviewed this study?

The school of Sport and Exercise Sciences Research Ethics and Advisory Group (REAG) at the University of Kent has provided ethical approval for this study.

## Who can I contact if I need to ask more questions about the study?

You can contact the research team at any time using the contact details below.

## Who can I contact if I want to complain about the study?

If you wish the complain about the way that the study was conducted, you can contact the Chair of the School of Science and Exercise Sciences Research Ethics and Advisory Group (REAG), Dr Karen Hambly (K.Hambly@kent.ac.uk).

## What should I do now?

If you require more information or if you are happy to participate, please contact Fiep Bargeman (fb228@kent.ac.uk).

## Research Team

| | |
|---|---|
| Fiep Bargeman (researcher) | fb228@kent.ac.uk |
| Lex Mauger (supervisor) | l.mauger@kent.ac.uk |
| Robert Barker (supervisor) | r.barker@kent.ac.uk |
| Irantzu Yoldi (external consultant) | i.yoldi@uel.ac.uk |

Appendix 9

SSES Consent Form 06/05/2022 Version 1

**Title of project: Foot Function Response to Terrain**

**Name & contact details of investigator & supervisor: Fiep Bargeman, fb228@kent.ac.uk and Lex Mauger, l.mauger@kent.ac.uk and Rob Barker, r.barker@kent.ac.uk**

**Participant name:**

**Participant identification number for this project:**

**Please initial box**

1. I confirm I have read and understand the information sheet version 1.1 for the above study. I have had the opportunity to consider the information, ask questions and have had these answered satisfactorily. ☐

2. I understand that my participation is voluntary and that I am free to withdraw at any time without giving any reason. If I wish to withdraw, I can contact Fiep Bargeman at fb228@kent.ac.uk ☐

3. I understand that my responses / data will be anonymised before analysis. I give permission for members of the research team to have access to my anonymised responses / data. ☐

4. I have read, understood and completed the Health Questionnaire honestly and to the best of my knowledge. ☐

5. I agree to take part in the above research project. ☐

| ______________________ | ______________________ | ______________________ |
|---|---|---|
| Name of participant | Date | Signature |

| ______________________ | ______________________ | ______________________ |
|---|---|---|
| Name of person taking consent *(if different from lead researcher)* | Date | Signature |

*To be signed and dated in presence of the participant*

| ______________________ | ______________________ | ______________________ |
|---|---|---|
| Lead researcher | Date | Signature |

**Copies:** ***(when completed) 1 for participant; 1 for researcher file.***

University of Kent

## HEALTH & SCREENING QUESTIONNAIRE (non-exercise studies)

**Participant Identification Number for this project:_______________**

Please answer these questions truthfully and completely. The sole purpose of this questionnaire is to ensure that you are in a fit and healthy state to take part in the study. **ANY INFORMATION CONTAINED HEREIN WILL BE TREATED AS CONFIDENTIAL.**

**Please read the questions below carefully and answer each one honestly. Please tick either YES or NO:**

| | YES | NO |
|---|---|---|
| 1. Has your doctor ever said that you have a heart condition or high blood pressure, which may affect exercise? | ☐ | ☐ |
| 2. Do you lose balance because of dizziness or have you lost consciousness in the last 12 months? (Please answer NO if your dizziness was associated with over-breathing including vigorous exercise). | ☐ | ☐ |
| 3. Have you had a viral infection in the last 2 weeks (cough, cold, sore throat, etc…. including COVID-19)? | ☐ | ☐ |
| If yes, please provide further details here: | | |
| 4. Have you ever been diagnosed with any chronic medical condition? | ☐ | ☐ |
| If yes, please list condition(s) here: | | |
| 5. Are you currently taking prescribed medications for a chronic medical condition? | ☐ | ☐ |
| If yes, please list condition(s) and medications here: | | |
| 6. Do you currently have (or have you had within the past 12 months) a bone, joint or soft tissue (muscle, ligament, or tendon) problem that could be made worse by becoming more physically active? Please answer NO if you had a problem in the past but it does not limit your ability to be physically active. | ☐ | ☐ |
| If yes, please provide further details here: | | |
| 7. Has your doctor ever said that you should only do medically supervised physical activity? | ☐ | ☐ |
| 8. Is there any other reason why you think you should not take part in this study? If yes, please give details below: | ☐ | ☐ |

Evaluation Measures

YOUTHREX
Research & Evaluation eXchange

# International Physical Activity Questionnaire - Short Form

**OVERVIEW**

- This measure assesses the types of intensity of physical activity and sitting time that people do as part of their daily lives are considered to estimate total physical activity in MET-min/week and time spent sitting.

**SUBSCALES**

- None
- Sample items from the scale:
  » During the last 7 days, on how many days did you do vigorous physical activities like heavy lifting, digging, aerobics, or fast bicycling?

**STEPPING UP THEME(S) & OUTCOME(S)**

- Health & Wellness
  » Youth are physically healthy

**TARGET POPULATION**

- Youth 15 years of age and older

**LENGTH & HOW IT IS MEASURED**

- 7 items
- Open-ended questions surrounding individuals' last 7-day recall of physical activity
- Self-report, paper-pencil version or orally
- Available in: English and many other languages

**DEVELOPER**

- International Physical Activity Questionnaire, 1998

**GOOD TO KNOW**

- Used by the Ontario Trillium Foundation
- Click here for Guidelines for Data Processing and Analysis of the International Physical Activity Questionnaire (IPAQ) - Short Form

**PSYCHOMETRICS**

- **Reliability**

  Test-rest reliability indicated good stability

  High reliability ($\alpha$ <.80)

- **Validity**

  Predictive validity

  Concurrent validity

  Convergent validity

  Criterion validity

  Discriminant validity

**LEARN MORE**


- International Physical Activity Questionnaire. (2016). Home. Retrieved from https://sites.google.com/site/theipaq/
- C.L. Craig, A. Marshall, M. Sjostrom, A. Bauman, M. Booth, B. Ainsworth, *et al*. International Physical Activity Questionnaire: 12-country reliability and validity. Med Sci Sports Exerc, 35 (2003), pp. 1381–1395
- Lee, P.H., Macfarlane, D.J., Lam, T.H., Stewart, S.M. (2011). *Validity of the international physical activity questionnaire short form (IPAQ-SF): A systematic review*. International Journal of Behavioral Nutrition and Physical Activity. 8:115.
- van Poppel MNM, Chinapaw MJM, Mokkink LB, van Mechelen W, Terwee CB: Physical activity questionnaires for adults: A systematic review of measurement properties. Sports Medicine. 2010, 40: 565-600. 10.2165/11531930-000000000-00000.

# INTERNATIONAL PHYSICAL ACTIVITY QUESTIONNAIRE (August 2002)

# SHORT LAST 7 DAYS SELF-ADMINISTERED FORMAT

## FOR USE WITH YOUNG AND MIDDLE-AGED ADULTS (15-69 years)

The International Physical Activity Questionnaires (IPAQ) comprises a set of 4 questionnaires. Long (5 activity domains asked independently) and short (4 generic items) versions for use by either telephone or self-administered methods are available. The purpose of the questionnaires is to provide common instruments that can be used to obtain internationally comparable data on health–related physical activity.

***Background on IPAQ***
The development of an international measure for physical activity commenced in Geneva in 1998 and was followed by extensive reliability and validity testing undertaken across 12 countries (14 sites) during 2000. The final results suggest that these measures have acceptable measurement properties for use in many settings and in different languages, and are suitable for national population-based prevalence studies of participation in physical activity.

***Using IPAQ***
Use of the IPAQ instruments for monitoring and research purposes is encouraged. It is recommended that no changes be made to the order or wording of the questions as this will affect the psychometric properties of the instruments.

***Translation from English and Cultural Adaptation***
Translation from English is supported to facilitate worldwide use of IPAQ. Information on the availability of IPAQ in different languages can be obtained at www.ipaq.ki.se. If a new translation is undertaken we highly recommend using the prescribed back translation methods available on the IPAQ website. If possible please consider making your translated version of IPAQ available to others by contributing it to the IPAQ website. Further details on translation and cultural adaptation can be downloaded from the website.

***Further Developments of IPAQ***
International collaboration on IPAQ is on-going and an ***International Physical Activity Prevalence Study*** is in progress. For further information see the IPAQ website.

***More Information***
More detailed information on the IPAQ process and the research methods used in the development of IPAQ instruments is available at www.ipaq.ki.se and Booth, M.L. (2000). *Assessment of Physical Activity: An International Perspective*. Research Quarterly for Exercise and Sport, 71 (2): s114-20. Other scientific publications and presentations on the use of IPAQ are summarized on the website.

# INTERNATIONAL PHYSICAL ACTIVITY QUESTIONNAIRE

We are interested in finding out about the kinds of physical activities that people do as part of their everyday lives. The questions will ask you about the time you spent being physically active in the **last 7 days**. Please answer each question even if you do not consider yourself to be an active person. Please think about the activities you do at work, as part of your house and yard work, to get from place to place, and in your spare time for recreation, exercise or sport.

Think about all the **vigorous** activities that you did in the **last 7 days**. **Vigorous** physical activities refer to activities that take hard physical effort and make you breathe much harder than normal. Think *only* about those physical activities that you did for at least 10 minutes at a time.

1. During the **last 7 days**, on how many days did you do **vigorous** physical activities like heavy lifting, digging, aerobics, or fast bicycling?

   _____ **days per week**

   ☐ No vigorous physical activities → ***Skip to question 3***

2. How much time did you usually spend doing **vigorous** physical activities on one of those days?

   _____ **hours per day**

   _____ **minutes per day**

   ☐ Don't know/Not sure

Think about all the **moderate** activities that you did in the **last 7 days**. **Moderate** activities refer to activities that take moderate physical effort and make you breathe somewhat harder than normal. Think only about those physical activities that you did for at least 10 minutes at a time.

3. During the **last 7 days**, on how many days did you do **moderate** physical activities like carrying light loads, bicycling at a regular pace, or doubles tennis? Do not include walking.

   _____ **days per week**

   ☐ No moderate physical activities → ***Skip to question 5***

4. How much time did you usually spend doing **moderate** physical activities on one of those days?

_____ **hours per day**

_____ **minutes per day**

☐ Don't know/Not sure

Think about the time you spent **walking** in the **last 7 days**. This includes at work and at home, walking to travel from place to place, and any other walking that you have done solely for recreation, sport, exercise, or leisure.

5. During the **last 7 days**, on how many days did you **walk** for at least 10 minutes at a time?

_____ **days per week**

☐ No walking → ***Skip to question 7***

6. How much time did you usually spend **walking** on one of those days?

_____ **hours per day**

_____ **minutes per day**

☐ Don't know/Not sure

The last question is about the time you spent **sitting** on weekdays during the **last 7 days**. Include time spent at work, at home, while doing course work and during leisure time. This may include time spent sitting at a desk, visiting friends, reading, or sitting or lying down to watch television.

7. During the **last 7 days**, how much time did you spend **sitting** on a **week day**?

_____ **hours per day**

_____ **minutes per day**

☐ Don't know/Not sure

**This is the end of the questionnaire, thank you for participating.**

**Additional Health Questionnaire as response to answering "yes" to Question 1 "*Has your doctor ever said that you have a heart condition or high blood pressure?*"**

Participant number:

1. Is the heart condition or high blood pressure chronic?
2. Has/ is the heart condition or high blood pressure (been) present recently / currently?
3. Does the heart condition or high blood pressure impact physical activity?
4. Do you feel comfortable walking for half an hour to an hour today?

Signed:

Date:

Signed Lead Researcher:

Date:

# Participant Data Sheet

Participant identification number:

**Part 1 will be filled in by the participant**

1) What is your age and what is your year of birth?

2) Do you have a walking/mobility impairment (e.g., you are a wheelchair user, you have a cast on one of your feet or experience pain while walking)?

The following question is asked to assess whether your assigned sex at birth corresponds with your current gender. This is because a higher level of oestrogen tends to influence the flexibility of ligaments and tendons. If you are uncomfortable answering this question, you can leave it blank.

3) What is your gender?

    a) Is it the same as your sex assigned at birth?

        i) Have you undergone any hormone treatment and was oestrogen one of those hormones?

4) Where did you live between the ages of 1-10 years old (if you've lived in multiple areas, please include the answers for as much as you can remember)?

    a) If can you remember the postcode, please state:

    b) If possible, please tell us whether you would consider that area / area you played on most as natural (woodland/field/nature) or developed (mostly paved ground):

**Part 2 will be filled in by the researcher**

- Height participant:
- Weight:
- Foot length:
- Truncated foot length:
- Dorsum height:
- AHI:
- FF:
- Type of shoe worn on the day:
    - Thickness of sole:

# Appendix 14

Overview of static measurements (dorsum height, truncated foot length) and the calculated values (arch displacement, spring constant, spring energy) used to discuss the foot's biophysics.

| FF | | Truncated Foot Length (m) | | | | Dorsum height (m) | | | | Horizontal arch displacement (m) | | Vertical arch displacement (m) | | | | Horizontal spring constant (N/m) | | Vertical spring constant (N/m) | | Horizontal spring energy (J) | | Vertical spring energy (J) | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| FF Right | FF Left | R Sitting | L Sitting | R Standing | L Standing | R Sitting | L Sitting | R Standing | L Standing | Xhr | Xhl | Xvr | Xvl | Δm (kg) | F (N) | Khr | Khl | Kvr | Kvl | Ehr | Ehl | Evr | Evl |
| 0.990 | 0.871 | 0.171 | 0.175 | 0.1715 | 0.1735 | 0.0685 | 0.066 | 0.068 | 0.057 | 0.0005 | -0.0015 | -0.0005 | -0.0090 | 28 | 137.34 | -274680 | 91560 | 274680 | 15260 | -0.034 | 0.103 | 0.034 | 0.618 |
| 0.910 | 0.832 | 0.165 | 0.1655 | 0.167 | 0.1645 | 0.076 | 0.075 | 0.07 | 0.062 | 0.0020 | -0.0010 | -0.0060 | -0.0130 | 34.2 | 167.751 | -83876 | 167751 | 27959 | 12904 | -0.168 | 0.084 | 0.503 | 1.090 |
| 0.964 | 1.021 | 0.1835 | 0.191 | 0.1835 | 0.187 | 0.083 | 0.0765 | 0.08 | 0.0765 | 0.0000 | -0.0040 | -0.0030 | 0.0000 | 39.2 | 192.276 | | 48069 | 64092 | | 0.000 | 0.385 | 0.288 | 0.000 |
| 0.941 | 0.971 | 0.189 | 0.189 | 0.19 | 0.192 | 0.0745 | 0.072 | 0.0705 | 0.071 | 0.0010 | 0.0030 | -0.0040 | -0.0010 | 37.6 | 184.428 | -184428 | -61476 | 46107 | 184428 | -0.092 | -0.277 | 0.369 | 0.092 |
| 0.837 | 0.862 | 0.201 | 0.195 | 0.212 | 0.206 | 0.077 | 0.073 | 0.068 | 0.0665 | 0.0110 | 0.0110 | -0.0090 | -0.0065 | 34 | 166.77 | -15161 | -15161 | 18530 | 25657 | -0.917 | -0.917 | 0.750 | 0.542 |
| 0.968 | 0.885 | 0.178 | 0.1735 | 0.175 | 0.172 | 0.062 | 0.065 | 0.059 | 0.057 | -0.0030 | -0.0015 | -0.0030 | -0.0080 | 22 | 107.91 | 35970 | 71940 | 35970 | 13489 | 0.162 | 0.081 | 0.162 | 0.432 |
| 0.947 | 0.836 | 0.176 | 0.179 | 0.183 | 0.184 | 0.067 | 0.064 | 0.066 | 0.055 | 0.0070 | 0.0050 | -0.0010 | -0.0090 | 24 | 117.72 | -16817 | -23544 | 117720 | 13080 | -0.412 | -0.294 | 0.059 | 0.530 |
| 0.899 | 0.877 | 0.182 | 0.175 | 0.184 | 0.186 | 0.077 | 0.074 | 0.07 | 0.069 | 0.0020 | 0.0110 | -0.0070 | -0.0050 | 29.6 | 145.188 | -72594 | -13199 | 20741 | 29038 | -0.145 | -0.799 | 0.508 | 0.363 |
| 0.962 | 0.880 | 0.1925 | 0.191 | 0.1915 | 0.19 | 0.07 | 0.072 | 0.067 | 0.063 | -0.0010 | -0.0010 | -0.0030 | -0.0090 | 38 | 186.39 | 186390 | 186390 | 62130 | 20710 | 0.093 | 0.093 | 0.280 | 0.839 |
| 0.805 | 0.963 | 0.18 | 0.18 | 0.185 | 0.183 | 0.081 | 0.073 | 0.067 | 0.0715 | 0.0050 | 0.0030 | -0.0140 | -0.0015 | 38 | 186.39 | -37278 | -62130 | 13314 | 124260 | -0.466 | -0.280 | 1.305 | 0.140 |
| 0.927 | 0.936 | 0.1705 | 0.17 | 0.1775 | 0.171 | 0.071 | 0.068 | 0.0685 | 0.064 | 0.0070 | 0.0010 | -0.0025 | -0.0040 | 22 | 107.91 | -15416 | -107910 | 43164 | 26978 | -0.378 | -0.054 | 0.135 | 0.216 |
| 0.932 | 0.884 | 0.192 | 0.194 | 0.202 | 0.198 | 0.077 | 0.082 | 0.0755 | 0.074 | 0.0100 | 0.0040 | -0.0015 | -0.0080 | 30.8 | 151.074 | -15107 | -37768 | 100716 | 18884 | -0.755 | -0.302 | 0.113 | 0.604 |
| 0.919 | 0.937 | 0.1795 | 0.182 | 0.179 | 0.1815 | 0.072 | 0.076 | 0.066 | 0.071 | -0.0005 | -0.0005 | -0.0060 | -0.0050 | 32.4 | 158.922 | 317844 | 317844 | 26487 | 31784 | 0.040 | 0.040 | 0.477 | 0.397 |
| 0.908 | 0.877 | 0.181 | 0.179 | 0.1815 | 0.183 | 0.078 | 0.077 | 0.071 | 0.069 | 0.0005 | 0.0040 | -0.0070 | -0.0080 | 32 | 156.96 | -313920 | -39240 | 22423 | 19620 | -0.039 | -0.314 | 0.549 | 0.628 |
| 0.946 | 0.926 | 0.183 | 0.1895 | 0.188 | 0.188 | 0.072 | 0.074 | 0.07 | 0.068 | 0.0050 | -0.0015 | -0.0020 | -0.0060 | 44 | 215.82 | -43164 | 143880 | 107910 | 35970 | -0.540 | 0.162 | 0.216 | 0.647 |
| 0.985 | 0.937 | 0.192 | 0.189 | 0.195 | 0.188 | 0.075 | 0.074 | 0.075 | 0.069 | 0.0030 | -0.0010 | 0.0000 | -0.0050 | 27.2 | 133.416 | -44472 | 133416 | | 26683 | -0.200 | 0.067 | 0.000 | 0.334 |
| 0.851 | 0.865 | 0.192 | 0.185 | 0.2 | 0.194 | 0.075 | 0.075 | 0.0665 | 0.068 | 0.0080 | 0.0090 | -0.0085 | -0.0070 | 27.2 | 133.416 | -16677 | -14824 | 15696 | 19059 | -0.534 | -0.600 | 0.567 | 0.467 |

# Appendix 15

Correlation coefficients of associations between FF and walking characteristics. Yellow fields indicate significant P-values. Plate (P), Developed (D), Natural (N), Power (W), Cadence (C), Step length (S), Neutral Pronation (PN), Footstrike total (FT), Velocity (MS). Guidelines were followed when choosing the right correlation test.

| Terrain | Category | Correlation coefficient Right foot FF and walking characteristic | P-value | Correlation coefficient Left foot FF and walking characteristic | P-value |
|---|---|---|---|---|---|
| Plate | **PP** | 0.13 | 0.618 | 0.35 | 0.166 |
| | **PC** | -0.10 | 0.701 | -0.42 | 0.097 |
| | **PS** | -0.10 | 0.693 | -0.25 | 0.338 |
| | **PPN** | -0.03 | 0.903 | 0.15 | 0.558 |
| | **PFT** | -0.07 | 0.784 | -0.10 | 0.699 |
| | **PFLR** | N/A | N/A | -0.14 | 0.596 |
| | **PFLM** | N/A | N/A | -0.28 | 0.280 |
| | **PFLF** | N/A | N/A | 0.22 | 0.398 |
| | **PFRR** | -0.01 | 0.960 | -0.04 | 0.885 |
| | **PFRM** | 0.16 | 0.544 | -0.24 | 0.355 |
| | **PFRF** | -0.21 | 0.422 | 0.42 | 0.093 |
| | **PMS** | -0.15 | 0.567 | -0.35 | 0.163 |
| Developed | **DP** | -0.08 | 0.760 | 0.38 | 0.134 |
| | **DW** | -0.09 | 0.739 | 0.08 | 0.753 |
| | **DE** | 0.21 | 0.422 | -0.26 | 0.307 |
| | **DC** | 0.27 | 0.302 | -0.30 | 0.242 |
| | **DS** | 0.02 | 0.954 | -0.30 | 0.243 |
| | **DPN** | -0.11 | 0.687 | 0.27 | 0.299 |
| | **DPLO** | N/A | N/A | -0.23 | 0.371 |
| | **DPLU** | N/A | N/A | 0.02 | 0.933 |
| | **DPLN** | N/A | N/A | 0.07 | 0.787 |
| | **DPRO** | 0.16 | 0.538 | N/A | N/A |
| | **DPRU** | 0.11 | 0.671 | N/A | N/A |
| | **DPRN** | -0.20 | 0.449 | N/A | N/A |
| | **DFT** | 0.16 | 0.537 | -0.33 | 0.192 |
| | **DFLR** | N/A | N/A | 0.05 | 0.849 |
| | **DFLM** | N/A | N/A | 0.15 | 0.556 |
| | **DFLF** | N/A | N/A | 0.07 | 0.804 |
| | **DFRR** | 0.06 | 0.813 | N/A | N/A |
| | **DFRM** | -0.11 | 0.680 | N/A | N/A |
| | **DFRF** | 0.13 | 0.631 | N/A | N/A |
| | **DMS** | 0.14 | 0.596 | -0.32 | 0.214 |
| Natural | **NP** | 0.06 | 0.820 | 0.49 | 0.047 |
| | **NW** | -0.22 | 0.397 | 0.32 | 0.204 |
| | **NE** | 0.25 | 0.324 | -0.41 | 0.099 |
| | **NC** | 0.16 | 0.545 | -0.24 | 0.363 |
| | **NS** | -0.16 | 0.541 | -0.56 | 0.021 |
| | **NPN** | -0.10 | 0.716 | 0.26 | 0.317 |
| | **NPLO** | N/A | N/A | -0.18 | 0.497 |
| | **NPLU** | N/A | N/A | -1.3e-03 | 0.996 |
| | **NPLN** | N/A | N/A | 0.22 | 0.403 |
| | **NPRO** | -2.5e-03 | 0.996 | N/A | N/A |
| | **NPRU** | -0.20 | 0.438 | N/A | N/A |
| | **NPRN** | -0.09 | 0.744 | N/A | N/A |
| | **NFT** | -0.09 | 0.729 | -0.11 | 0.663 |
| | **NFLR** | N/A | N/A | -0.16 | 0.547 |
| | **NFLM** | N/A | N/A | 0.24 | 0.344 |
| | **NFLF** | N/A | N/A | -0.07 | 0.793 |
| | **NFRR** | -0.04 | 0.892 | N/A | N/A |
| | **NFRM** | 0.07 | 0.789 | N/A | N/A |
| | **NFRF** | -0.04 | 0.888 | N/A | N/A |
| | **NMS** | -0.05 | 0.853 | -0.52 | 0.032 |

# Appendix 16

Correlation coefficients of associations between terrains per walking characteristics and between walking characteristics. Yellow fields indicate significant P-values. Plate (P), Developed (D), Natural (N), Power (W), Cadence (C), Step length (S), Neutral Pronation (PN), Footstrike total (FT), Velocity (MS). Guidelines were followed when choosing the right correlation test.

| **Category** | **Variables** | **Correlation coefficient** | **P-value** |
|---|---|---|---|
| Power | **DW, NW** | 0.62 | 8.1e-03 |
| Cadence | **PC, DC** | 0.67 | 3.1e-03 |
| | **PC, NC** | 0.69 | 2.4e-03 |
| | **DC, NC** | 0.79 | 1.8e-04 |
| Step length | **PS, DS** | 0.50 | 0.040 |
| | **PS, NS** | 0.48 | 0.050 |
| | **DS, NS** | 0.76 | 4.3e-04 |
| Pronation | **PPN, DPN** | 0.85 | < 2.2e-16 |
| | **PPN, NPN** | 0.80 | 1.8e-04 |
| | **DPN, NPN** | 0.86 | < 2.2e-16 |
| Footstrike total | **PFT, DFT** | -0.54 | 0.024 |
| | **PFT, NFT** | -0.20 | 0.437 |
| | **DFT, NFT** | 0.27 | 0.303 |
| Velocity | **PMS, DMS** | 0.44 | 0.078 |
| | **PMS, NMS** | 0.55 | 0.023 |
| | **DMS, NMS** | 0.63 | 6.7e-03 |
| Footstrike total/ Step length | **PFT, PS** | 0.58 | 0.015 |
| | **NFT, NS** | 0.08 | 0.754 |
| | **DFT, DS** | 0.47 | 0.054 |
| Footstrike total/ Pronation | **PPN, PFT** | 0.12 | 0.649 |
| | **DPN, DFT** | -0.23 | 0.372 |
| | **NPN, NFT** | -0.19 | 0.459 |
| Footstrike total/ Cadence | **PFT, PC** | -0.36 | 0.160 |
| | **DFT, DC** | 0.49 | 0.044 |
| | **NFT, NC** | 0.18 | 0.496 |
| Footstrike total/ Power | **DFT, DW** | -0.06 | 0.807 |
| | **NFT, NW** | -0.15 | 0.571 |
| Footstrike total/ Velocity | **PFT, PMS** | 0.32 | 0.207 |
| | **DFT, DMS** | 0.65 | 4.9e-03 |
| | **NFT, NMS** | 0.10 | 0.697 |
| Power/ Cadence | **DW, DC** | -0.17 | 0.517 |
| | **NW, NC** | -0.28 | 0.281 |
| Power/ Step length | **DW, DS** | 0.02 | 0.948 |
| | **NW, NS** | -0.18 | 0.500 |
| Power/ Pronation | **DW, DPN** | 0.41 | 0.102 |
| | **NW, NPN** | 0.27 | 0.286 |
| Power/ Velocity | **DW, DMS** | 0.02 | 0.931 |
| | **NW, NMS** | -0.27 | 0.300 |
| Cadence/ Step length | **PC, PS** | 0.28 | 0.277 |
| | **DC, DS** | 0.19 | 0.463 |
| | **NC, NS** | 0.31 | 0.233 |
| Cadence/ Pronation | **PC, PPN** | -0.02 | 0.936 |
| | **DC, DPN** | -0.38 | 0.136 |
| | **NC, NPN** | -0.40 | 0.109 |
| Cadence/ Velocity | **PC, PMS** | 0.61 | 8.8e-03 |
| | **DC, DMS** | 0.73 | 8.2e-04 |
| | **NC, NMS** | 0.71 | 1.5e-03 |
| Step length/ Pronation | **PS, PPN** | -0.11 | 0.677 |
| | **DS, DPN** | 0.04 | 0.866 |
| | **NS, NPN** | -0.20 | 0.439 |
| Step length/ Velocity | **PS, PMS** | 0.92 | 1.3e-04 |
| | **DS, DMS** | 0.77 | 2.9e-04 |
| | **NS, NMS** | 0.89 | 1.8e-06 |
| Pronation / Velocity | **PPN, PMS** | -0.18 | 0.479 |
| | **DPN, DMS** | -0.27 | 0.296 |
| | **NPN, NMS** | -0.31 | 0.220 |