Analysis of plantar pressures to explore real-world functional characteristics and development of the infant weight-bearing foot

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A thesis submitted in partial fulfilment of the requirements of the University of Brighton for the degree of Doctor of Philosophy

July 2022

Abstract

The field of plantar pressure is poorly explored in developmental biomechanics, with scarcity of studies investigating functional characteristics and development of the infant weight-bearing foot. Specifically, the available research has focussed on plantar pressures captured from systematic gait protocols, ignoring data captured in real-world settings, and using discrete statistical approaches for the analysis. This thesis investigated foot function characteristics and development of 39 typically developing infants, as they attained three stages of motor development, namely pull to stand, the onset of walking and confident walking. This was achieved by a thorough analysis of plantar pressures originating from one of the largest data set collected in infancy, in a real-world, free-walking environment, implementing novel discrete and continuous approaches to plantar pressure data analysis. After the appropriateness of such methodologies have been established in this thesis, it has been demonstrated that 33 infants at the three stages of motor development showed unique yet common pressure patterns that perpetuated from pull to stand to confident walking (e.g., greater involvement of the forefoot regions, highest pressure applied in the heel). The application of pressure and its changes throughout stance were investigated through vector fields' analysis of centre of pressure (COP) in 39 infants with Statistical Parametric Mapping (SPM). This chapter demonstrated changes in the anterior-posterior and medio-lateral components of the COP that underpinned modification of foot-ground interactions, occurring with a more stable and controlled foot placement towards the ground in confident walking stage. Finally, analysis of plantar pressures with SPM demonstrated increasing pressure in the medial heel, in the lateral and central forefoot, as well as decreasing pressure in the hallux and in the medial midfoot, highlighting that body weight and walking experience significantly predicted plantar pressure changes during walking in infancy. As a result, this thesis demonstrated, for the first time, that typical patterns of foot function in walking originates from early stages of bipedal upright locomotion. Alongside a cascade of complex neuromuscular-skeletal maturation, plantar pressures demonstrated also the quick establishment of the typical yet immature rollover pattern of the foot from the onset of walking, which originates after 2.3 months of independent walking experience. With this information, this thesis provided a set of typical developing data that can be used in both research and clinical practice to develop and improve future studies, enhance foot assessment as well as improve knowledge that can help interpret clinical findings and make decisions.

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Acronyms

0-dimensional	0D

1-dimensional	1D
2-dimensional	2D
3-dimensional	3D
Anterior-posterior	AP
Body mass index	BMI
Central pattern generator	CPG
Coherent point drift	CPD
Confidence Interval	CI
Contact area	CA
Contact time	CT
Central nervous system	CNS
Centre of Pressure	COP
Centre of Mass	COM
Force time integral	FTI
Ground reaction force	GRF
Iterative closest point	ICP
Interclass-correlation coefficient	ICC
Interquartile range	IQR
Maximum Force	MaxF
Maximum pressure picture	MPP
Medial longitudinal arch	MLA
Medio-lateral	ML
Peak pressure	PP
Pressure-time integral	PTI
Pedobarographic Statistical Parametric Mapping	pSPM

Region of interest	ROI
Roll-over process	ROP
Root mean square error	RMSE

Acknowledgements

First and foremost, I would like to express my most sincere appreciation to the guidance received during this PhD journey by my two supervisors, Dr. Stewart C Morrison and Dr. Carina Price. With your relentless and continuous support in these three years, I have been able to overcome many challenges related to the completion of this thesis, you have always encouraged me to pursue my ideas and inspire the type of researcher I want to become. I could not ask for better supervisors.

A big thank to the entire Great Foundation team, in particular Dr. Chris Nester, Dr. Ana Martinez Santos, Molly Hodges and Lisa Hodgson for their support, in particular during the most challenging recruitment and data collection sessions.

I would also like to describe how thankful I am to my friend and colleague Dr. Matyas Varga, for his continuous inputs, feedback and support that helped me develop a more analytical mind. I definitely owe you my programming skills.

I would also like to spend some words to thank Dr. Juliet McClymont, who I firstly met when I joined the Great Foundation team and who provided me with the curiosity that pushed me to pursue a Doctoral degree.

Part of the merit for achieving this milestone goes to my family, who supported and believed in me without hesitation, and allowed me to undertake this journey in the UK back in 2017.

This dedication goes to the companions I chose to share this journey with, my friends. Specifically, I would like to thank Igor, Pasqua for the days spent working in Pomodoro, the laughs, and all the moments that cheered me up. In addition, a big thank to Beatrice, Giorgia, Giulia e Valeria for having the patience to deal with my absence, but yet having time to comfort me when I needed.

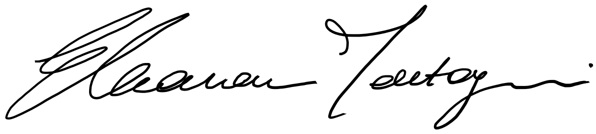
I would like to thank Giacomo, who was the first pushing me to pursue this journey even though it meant for us to be separated for a while at the time.

Finally yet importantly, I would like to thank Claudio, who helped me throughout this journey and managed to make linear algebra a real fun.

Authors' statement

This PhD is part of the Great Foundation project led by Prof Christopher Nester (University of Salford) and Dr Stewart Morrison (University of Brighton). Precisely, this PhD originates from the Small Steps study (Price et al., 2018a), and funding was provided by the William M. Scholl Endowment Fund. I declare that the research contained in this thesis, unless otherwise formally indicated within the text, is the original work of the author. The thesis has not been previously submitted to this or any other university for a degree, and does not incorporate any material already submitted for a degree.

Dated: 26.07.2022

Signed: 

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Chapter 1. Thesis overview

1.1 Introduction

The foot is a complex structure composed by over 26 bones, 30 joints and over 100 muscles, ligaments and tendons. During infancy and childhood, multiple body systems continuously develop such as the neurological, sensory and musculoskeletal systems (Adolph et al., 2003). Such changes considerably influence infants and children postural control and motor changes (Malina, 2003) and underpin foot development (Lacquaniti et al., 2012). Consequently, infants progressively learn, perform and master a series of different non weight-bearing and weight bearing motor tasks, such as grasping and playing with feet, pulling up to stand and walking independently, which represent specific developmental milestones (Adolph et al., 2003). During attainment of these milestones, the foot starts bearing weight cyclically and being involved in several biomechanical motor behaviour (Bisi and Stagni, 2015), fulfilling different functions. As an example, it has been demonstrated that new-borns use their feet to reach for toys instead of using their hands (Galloway and Thelen, 2004). The feet of new-borns are also used as a sensory organ, to provide information regarding the position of infants in space (Thelen, 1995).

The uniqueness of the infant foot is therefore an essential aspect of developmental biomechanics, although it is still poorly understood. Among the different technologies available, plantar pressure assessment is considered as an important resource in biomechanical research (Rosenbaum and Becker, 1997). Accordingly, analysis of plantar pressures patterns and their changes across infancy would enable the description of the typical foot function characteristics and its development during the attainment of weight bearing motor tasks. However, research analysing plantar pressures in infants has been carried out only from the onset of walking (e.g., infants taking first steps and often fall down/lose balance while walking) (Bisi and Stagni, 2015, Hallemans et al., 2003, Bertsch et al., 2004), with lack of investigations tracking plantar pressure patterns prior to independent walking. In addition, plantar pressure research in infancy have been carried out adopting testing protocols inherited from studies facilitating systematic analysis of adult walking, missing the real-world motor behaviour of infants. This is an important aspect of developmental science, with research demonstrating the importance to capture the inter-individual variability of habitual movement patterns without constraints infants to perform specific motor tasks (e.g., walking from specific start and ending point in straight-line) (Adolph et al., 2018). Furthermore, studies have mainly explored plantar pressure patterns during walking using different pressure variables, such as contact areas, contact times and peak pressures. These parameters were, however, reported inconsistently among the studies, and calculated as average values within regions of the foot (e.g., the heel, the forefoot), which were also selected arbitrarily.

Current interpretations of plantar pressure data are therefore limited due to the low-resolution methodologies to data processing and analysis that does not consider pressure data in their continuous spatial domain. Accordingly, the easiest and most commonly used interpretative analysis for plantar pressure is by region of interest, which has been shown to reduce the spatial resolution of pressure data and to conflate statistical conclusions along regional boundaries (Pataky and Goulermas, 2008). In addition, hardware designs for masking analyses are almost exclusively scaled for the typical rollover pattern of the foot and consistent contact area practiced habitually step-to-step by adults. Such approach is also not representative of the underlying pressure field produced with by foot-ground interactions, as there are no boundaries on the plantar surface implying functional independence of anatomical areas of the foot (Pataky et al., 2008a).

Despite this, changes in plantar pressure parameters have also been investigated alongside considerations related to their relationship with increasing body weight and height in infancy (Bosch et al., 2010). Such investigations are important as they allow researcher to explore which are the best variables to predict pressure changes. Nevertheless, these analyses are scarce in infancy, with only Bosch et al. (2010) reporting it to predict changes in pressure over a nine-year period of observation, which were therefore not focussed on infancy-specific maturation and developmental processes and used, again, discrete statistical methods.

Apart from regional data, studies have reported also centre of pressure data to determine the patterns of pressure application and its changes with more walking experience (Bertsch et al., 2004, Hallemans et al., 2003, Hallemans et al., 2006b). Such investigation were however carried out mainly through visual observation of the data as well as discretisation of the continuous spatial domain of the centre of pressure trajectories, which were considered as average values as opposed to vectors. As a result, plantar pressure information has been, once again, sacrificed due to the low-resolution analytical approaches that did not consider pressure changes in the spatial domain of the data.

Consequently, the study of infant pressure data is at a risk of conflation due to testing protocols, data collection and methodologies lacking in-depth considerations of plantar pressures as analytical approaches that did not consider the meaningful spatial domain of pressure data. As a result, thorough investigation of the characteristics of foot function associated with exploration of its development throughout infancy have not been fully reported. Therefore, the aim of this PhD study will be to investigate foot function characteristics and its development from pull to stand to the transition to confident and independent walking. Specifically, this project will provide, for the first time, a robust, high-resolution investigation of plantar pressure data collected in free-walking environment and captured from a longitudinal design, as the foot develops from a newly weight bearing complex, into a fully weight bearing structure. This PhD will also account for large inter-individual datasets, enabling to capture the biomechanical transition to a plantigrade posture and providing valuable insights for the research community as well as clinicians in order to understand the typical development of foot function as it becomes a weight bearing structure.

1.2 Thesis aims and structure

The overarching aim of this PhD will be to investigate plantar pressure data to explore the characteristics and development of typical foot function in the transition from pull to stand to confident walking. This will be achieved by adopting a longitudinal design and a testing protocol to capture real-world plantar pressures at different stages of motor development. In order to evaluate this, the thesis will focus on four different objectives (representing the four main experimental chapters of this thesis), each of them presenting a series of sub-objectives, which can be summarised as follow:

i. **To establish the optimal approach(es) to analysis and interpretation of plantar pressure data in infancy (chapter 4).** The aim of this work will be to investigate different methodological approaches adopted in the field of plantar pressure analysis, applying them to a preliminary set of infants' pressure data, to provide a solid and robust framework to build the larger analysis within this thesis. As a result, the following objectives will be investigated:
   - Comparison of two automatic masking approaches to analyse plantar pressure data in infancy.
   - Pedobarographic statistical parametric mapping of plantar pressure data in new and confident walking infants: a preliminary analysis.

ii. **Describing plantar pressure patterns in the development of bipedal, independent locomotion (chapter 5).** In this chapter, pressure data of infants will be described to determine the typical foot function characteristics in the attainment of three different milestones, namely when infants pull to stand, start to walk independently and walked confidently and independently. This chapter will use a large intra and inter-individual data set and a novel masking analysis approach created according to the infant-specific foot proportions.

iii. **Investigating patterns and changes of foot-ground interaction through vector fields' analysis of centre of pressure data from the onset of walking to confident walking stages (chapter 6).** In this chapter, the centre of pressure trajectories will be investigated using continuous statistical analysis, to detect patterns of pressure application and their changes with respect to the entire stance, associating considerations related to mean path lengths and velocities of medio-lateral and anterior-posterior components of the centre of pressure. In this chapter, the following objectives will be addressed:
   - Statistically compare the medio-lateral and anterior-posterior trajectories, mean path length and velocity of the centre of pressure between infants at the onset of walking and confidently walking.

- To identify the presence of plantar pressure distribution changes with respect to stance phase.

iv. **Exploring changes in plantar pressures and their relationship with body maturation and walking experience (chapter 7).** This chapter will focus on comparing plantar pressures between the onset of walking and confidently walking, as well as establishing the relationship between factors related to body maturation and walking experience with plantar pressures. This will be achieved using an advanced statistical approach for 2-dimensional continuous analysis of pressure data. This chapter will enable to capture where changes in plantar pressures occurred in the transition to confident walking, with potential to understand which factors should be accounted for to predict plantar pressure changes.
As a result, the following objectives will be addressed:
   - To statistically compare between pressure data of infants at the onset of walking and confidently walking.
   - To establish the influence of maturation (increasing foot length, height, foot width, and foot proportions) and walking experience to plantar pressures.

The thesis will conclude with a discussion of the findings (chapter 8), where research and clinical implications, limitations of the works, conclusion and future directions will be reported.

Chapter 2. Literature review

This chapter of the thesis will present an extended literature review on paediatric development and foot biomechanics. Specifically, the review will offer an initial introduction to paediatric growth and development (section 2.1), with particular focus on the changes in the motor and postural control systems (section 2.1.1). The section will progress with considerations about postural changes of the lower limb (section 2.1.2) and foot development (section 2.1.3), followed by an overview of paediatric gait characteristics and changes across infancy and childhood (section 2.1.4).

Subsequently, the literature will be investigated with respect to approaches to analyse foot biomechanics (section 2.2). The section opens with introductory concepts (section 2.2.1), data collection (section 2.2.2) and analysis (section 2.2.3) of plantar pressure data. This will aim to demonstrate strengths and limitations of the available approaches to pressure data collection and analysis in infants and inform their application to paediatric samples.

The available literature relating to plantar pressure analysis in infancy (section 2.3.1) and childhood (section 2.3.2) will be then reported and changes in pressure patterns in infants and children discussed (section 2.3.3), in order to illuminate the existing knowledge regarding paediatric foot function development. Extending the review to plantar pressure data in childhood will help highlight findings from a wider variety of paediatric studies that enabled to track the weaknesses and strengths of the studies protocols to improve future works. This section will terminate with considerations regarding the relationship of several developmental factors (e.g., age, body weight) with plantar pressures. This part of the section will clarify whether these variables are important predictors in plantar pressure analysis and if they should be considered to enhance understanding of foot function development in infancy and childhood. In addition, gaps and limitations of the available literature will be highlighted (section 2.3.4) and common conditions affecting the infant foot will be summarised (section 2.3.5), in order to provide information regarding the clinical relevance of using plantar pressure assessment in clinical populations.

2.1 Paediatric growth and development

The paediatric age represents a period of continuous growth and development, when changes in several body systems occur such as neurological and musculoskeletal. In paediatrics, “growth”, also referred to as maturation, identifies structural and physiological changes, for example in body weight or height, whilst “development” is a continuous and gradual process that combines aspects of growth with external factors that could influence it, such as the environment (Feldman, 2006). The development of infants and children's populations is characterised by the interactions between genetically controlled processes and environmental factors (Plomin and Asbury, 2005), as age itself do not cause development (Feldman, 2006). Accordingly, age can be considered as just a chronological representation of growth, and it accounts for unspecified developmental processes occurring in several body systems (e.g., neurological, sensory, and musculoskeletal).

Genetic aspects of growth include changes in body proportion such as increasing brain size, weight, and height, whilst environmental factors include social, emotional, and cognitive experiences, as well as diet or exposure to pathological conditions (Mercer, 1998). Within the paediatric age, boundaries of infancy and childhood can be identified such as new-borns (0-4 weeks), infants (4 weeks-12 months), toddler (12-24 months of age), pre-school children (2-5 years), and school-aged children (6-13 years of age) (Kail, 2001). These boundaries also represent periods of development, as psychological, emotional as well as gross and fine motor development occurs as infants, and children grow.

Developmental milestones, defined as periods of cognitive and physical growth, mark the development of infants and children, such as their ability to walk and understand verbal language. From the motor learning perspective, several fundamental milestones take place during the first two years of life that represent the baseline for differentiation of more complex motor tasks. Infants learn how to control the head (0-3 months), sit without support (3-5 months of age), roll over (5-7 months of age), and pull up to stand and cruise (7-9 months of age). Around the age of 10-11 months, infants also start to walk supported and reach the stage of independent walking between the ages of 12-14 months. These can be identified as windows of typical development, although their attainment can be flexible and not always present in the same order among infants and children (Group and de Onis, 2006). Milestone attainment occurs due to the presence of dynamical systems that interconnect the genetic-environmental factors to the motor tasks performed (Thelen and Smith, 1994; Lewis, 2000). Therefore, in the following sections, an extensive review of the processes that contribute to the development of motor skills in infancy will be reported, in order to increase understanding of the mechanisms related to development of locomotion.

2.1.1 Motor development and postural control

At birth, infants are relatively sedentary, and gradually acquire competences in motor activities, which are dependent upon development of neuro-muscular anatomy and physiology (Malina, 2003). Voluntary movements develop during the first two years of life, when development of the postural control system is pivotal for the establishment of independent dynamic tasks such as walking (Bril and Brenière, 1993). Postural control is referred to as the ability to integrate controlled movements into sequences necessary to maintain balance and upright posture, and eventually progress forward (Ivanenko and Gurfinkel, 2018). These tasks are achieved by gradually controlling and stabilising the position of the centre of mass (COM) between the feet, representing the base of support (Horak, 1992). A typically developed postural control system is characterised by two main units: the reactive postural adjustment (RPA) and the anticipatory postural adjustment (APA). The RPA is defined as the mechanism that allow reactions to unexpected external perturbations, while the APA refers to the anticipation of internal perturbations caused by production of voluntary movements (Westcott and Burtner, 2004). These units are gradually developed through changes within the (i) neuro-motor, (ii) sensory and (iii) musculoskeletal systems, which take part in enhancing coordination of postural activity (Westcott and Burtner, 2004).

(i) The neuro-motor system participates in the activation of the muscles necessary to move and maintain balance. This is dependent upon development of the central nervous system (CNS). Specifically, the brain in new-borns is 1/3rd the size of adults' brain, and during the first 10 months of age, it increases considerably, to reach 70% of its total final size around two years of age (Adolph et al., 2003). This dramatic growth has been defined also as brain growth spurt, which continues up to the four years of age (Malina, 2003). During infancy, brain growth spurt is influenced by the physiological development of the glial cells, synapsis and axons, also referred to as nerve fibres, which constitute the projection of neurons and are involved in conducting electrical signal from neurons to the overall CNS. On the histological perspective, axons within the CNS lack of myelin (Eyre et al., 2000). Myelin is a fatty tissue that thickens around the axons and increases the speed of the electrical signals that run through the axons. If the axon is unmyelinated, the signal is slow but the greater the thickness around the axons, the quicker is the transmittal of electrical signals within the CNS (Eyre et al., 2000). Apart from overall brain growth, postural development is also influenced by growth of several neurological structures, such as the cerebellum, and the structures descending from the cortex to the spinal cord, such as neocortex and motor tracts (Martin, 2005). Both cerebellum and corticospinal tracts are highly immature and unstable at birth (Yang et al., 2004). The cerebellum is the structure of the CNS that is involved in development and maintenance of coordination, equilibrium and muscle tone. According to Malina (2003), the cerebellum is one of the first structures within the CNS to complete its growth, reaching adults’ size by the 18 months of age. In this period of infancy, independent walking is also achieved.

In combination with the maturation of the cerebellum, changes within the corticospinal tract also take place during the first two years of life (Martin, 2005; Yang et al., 2004). The main function of the corticospinal tract is to control voluntary movement of the lower limb, reaching and manipulation (Porter and Lemon, 1993). Axons’ size within the corticospinal tract of new-borns however are 10 times smaller in comparison with adults (Eyre et al. 2000) and myelin tissue does not fully develop until the two years of age (Holmes et al., 2012). Due to the immature CNS structures, the motor system is undeveloped and lack of volition at birth (Malina, 2003). For example, new-borns normally alternate simple flexion and extension of the legs through co-activation and co-contraction of leg muscles (Okamoto et al., 2001), as opposed to the sparser muscles activation in adults (Ivanenko et al., 2006). The stepping pattern in new-borns is mediated at spinal cord level that take the form of reflexes described as being very similar to walking (Verbruggen et al., 2016). These reflexes are generated due to the presence of a specific and independent neural circuit called innate central pattern generator (CPG) (Yang et al., 2004). A CPG is a system of neurons present in both limbs that activates motor neurons, which innervate flexors and extensors of the lower limbs (Clark and Phillips, 1993). In absence of input from supra spinal or sensory systems, the CPGs causes rhythmical movement patterns of the lower limb that resemble walking (Clark and Phillips, 1993). Higher neural centres gradually inhibit these patterns as the CNS develops and are integrated into more controlled and complex movements as well as motor patterns, (Malina, 2003), leading to the establishment of refined and independent tasks such as walking.

(ii) Acquisition and refinement of postural control occur also because of the development of the somatosensory system. The somatosensory system is part of the sensory nervous system, and it comprised of several receptors such as nociceptors, mechanoreceptors and proprioceptors, which informs about changes of the body in relation to external stimuli.

Among these senses, proprioception enables infants and children to locate themselves into space and maintain balance, and it enables to move successfully in response to perturbations or movement (Dunn, 1999). Thus, the developing proprioception system helps infants and children integrate fundamental and complex movements in a controlled fashion (Jiang et al., 2016). The proprioceptive system is made of small receptors called mechanoreceptors (e.g., muscles spindles) and proprioceptors (Golgi tendon organs) within joints, muscles and tendons that control changes occurring at muscles and tendon levels such as compression, tension and stretching (Tarakci, 2016). Muscles spindles are the most common sensory receptors within body muscles, informing the CNS about changes in length, and stretch occurring at each muscle levels (Shaffer and Harrison, 2007). Through the information received from muscles spindles, the CNS capture where in the space the body moves (Kristjansson and Treleaven, 2009), which is an essential requirement for motor development and postural control. Development of proprioceptive feedback has been reported to be triggered by initiation of movements in infancy, and continues to improve throughout childhood (Elliot et al., 1988), as myelinisation continues and increases neural conductivity within the nerve fibres of mechanoreceptors.

(iii) Development of postural control is also dependent upon changes within the musculoskeletal system, which provide the necessary starting point to allow movements and generate the forces to produce the muscles activity involved in maintain balance (Westcott and Burtner, 2004). Specifically, the musculoskeletal system is composed of adipose and connective tissue, bones, and soft tissues, such as tendon and ligaments, which are innervated and vascularised. The adipose tissue provides protection from external forces, stores energies and produce body heat (Kershaw and Flier, 2004). During the first nine months of life, body adipose tissue increases in thickness, with a consequent drop in growth, so that by the five years of age, it is half-thick compared to the nine-month-old infants (Huelke, 1998). Overall, the skeletal system provides the structure that allow humans to move in space, offers protection and it is the site of mineral storage and production of blood cells (Stalheim-Smith and Fitch, 1993). Bones of the lower limbs develop faster in comparison with the upper limbs: at birth, 15% of the total body volume is occupied by the skeleton of the lower limb, which reaches 30% of the total body volume in adults (Huelke, 1998). On the contrary, the upper limbs occupy only 8% of the total body volume and this proportion remain throughout the entire life (Huelke, 1998). The lower limb is composed of hip, thigh, knee, ankle, and foot, which includes a series of short, long, sesamoids and accessory bones, if present. Long bones, such as femur and tibia are tubular, whilst short bones can be described as cuboidal, such as the tarsal bones. Sesamoid bones forms in proximity of tendons (e.g., patella), to assist their lever actions during movement.

During growth, the bones are remodelled by the actions of bones cells such as osteoblasts and osteoclasts. These cells deposit and model bone depositions in the bone's epiphysis (terminal part of the bone) and diaphysis (shaft of the bone), leading to a decreased amount of cartilage and absorption of ossification centres (Breeland et al., 2020). This process is called ossification and defines development in hardness of the lower limb and foot bones and closure of their growth plate present. Bones of the foot and lower limb present two types of ossification centres: primary and secondary (Moore and Dalley, 1999). When primary ossification centres are ossified, the skeletal structure start to be more robust. The ossification process starts around the sixth/seventh week of embryonic period and continue up to the age of 25 (Breeland, 2020). During this time, the ossification process starts within the long and bigger bones, and it is gradually extended to the smaller, short bones (Hubbard et al., 1993).

2.1.2 Postural development of the lower limb

After birth, the lower limb undergoes several postural changes, which are the result of development of the lower limb posture in utero. Specifically, the last trimester of pregnancy is characterised by the hips in abduction, flexion of the knees, internal rotation of the tibia, dorsiflexion of the ankles, and adduction of the feet (Evans, 2010). In the sagittal plane, the hips pass from 30 to zero degrees of flexion from birth to the age of three years. The knees also lose the 30 degrees flexion position and straighten up during the first six months of age, leading to a gradual extended position of infants in 10-16 months (Evans, 2010). Moreover, the ankles at birth are characterised by 40 degrees dorsiflexion, which drop to 5-10 degrees during independent walking.

In the frontal plane, the hips are in abducted position, which pass from 75 to 45 degrees during the first two years of life, resembling adults’ hip position (Evans, 2010; Hallemans et al., 2005). New-borns also present a 15 degrees genu varus (Schuster and Skliar, 1991), with femur and tibia in external and internal rotation, respectively. This position of the lower limb is physiological and remain throughout infancy (Magee, 2002), providing aids during the establishment of independent walking by increasing the base of support and mitigating the lack of balance. The position of the knee in the frontal plane change between the age of two and seven years. Specifically, by the age of 18 months, the femur and tibia are expected to reach a more natural position, with the external rotation of the tibia causing the femur to rotate internally and its condyles to move closer (McCarthy and Drennan, 2009). These processes bring about changes in the knee position in the frontal plane, which passes from varus to valgus around the age of two years (Evans, 2010). The maximal valgus knee position is reached at the age of three, and gradually decrease up to the six years, when the knee straightens up in relation to the leg (McCarthy and Drennan, 2009). At birth, the tibial-femoral angle is around 15-17 degrees, but changes to 11-degrees valgus by the age of three years. From the three to nine years of age, the tibial-femoral angle reaches the 6 degrees in valgus (Lehman, 2010), with studies reporting that 7-degrees valgus are already reached by the age of seven years. In the frontal plane, the subtalar joint is also in a 10-degree varus position relative to the leg at birth. Alongside the subtalar joint, the forefoot is also in a 10–15-degrees varus position relative to the calcaneus at birth. During the first year of life, the calcaneus reaches 10-degree eversion position, which reduces during the first six to eight years (Lehman, 2010). Postural development of the lower limb continues up to 20 years (Beeson and Nesbitt 2002, pp. 343). With lower limb posture development, the foot also undergoes major structural and morphological changes during infancy and childhood, which will be discussed in the following section.

2.1.3 Foot growth and development

At birth, the foot is a non-weight bearing structure that fulfils different functions and plays an important role in enhancing exploration of the surrounding environment and interaction with others. Between 8 to 15 weeks of age, for example, it has been demonstrated that infants use their feet in a coordinated way and to reach for toys instead of using their hands (Galloway and Thelen, 2004). Moreover, infants also use the foot as a sensory organ, as it helps locate them themselves in space (Thelen, 1995). During infancy and childhood, several developmental processes occur within the foot as reported in the following sections.

2.1.3.1 Maturation of foot structures and dimensions

The foot is characterised by the presence of 28 bones, in a combination of long and short (Kelikian and Sarrafian, 2011). At birth, these bones are small, characterised by the presence of ossification nuclei and cartilage (Butterworth and Marcoux, 2019). Specifically, diaphysis of the metatarsals is present already from birth, but epiphyses are made of cartilage that decreases during growth. Ossification within the bones of the foot initiates prenatally, specifically in the distal phalanx of the hallux, which is followed by the metatarsal bones, the distal and proximal phalanges of the lesser toes and it concludes with the middle phalanges (Hubbard et al., 1993). Within the first three and fifth prenatal months, the ossification of the forefoot terminates (Kelikian and Sarrafian, 2011). After birth, the ossification within the foot starts with the talus, calcaneus, and the cuboid, which ossify by 55%, 62% and 70% respectively at three months of age (Hubbard et al., 1993). The ossification centre of the cuneiforms and the navicular appear between two to three years of age, and do not fully ossify until five years of age (Hubbard et al., 1993). Ossification of the foot bones occurs within the first 10 years of life, although full closure of the growth plate take place between 15 and 21 years.

Soft tissues, such as ligaments and tendons are also characterised by small numbers of crosslinks among their tissue fibres, which cause the foot to be highly flexible and lax (Fritz and Mauch, 2013). An increase in number of these crosslinks contributes to define a more rigid and fixed structure, characteristic of a typically developed foot (Pfeiffer et al., 2006). This process generally starts between the two to four years of age, with a full consolidation occurring during adolescence (Walther et al., 2005). Muscles within the lower limb also start to strengthen after birth, due to exposure to a new gravitational environment, and continue to develop in strength throughout infancy and childhood (Fritz and Mauch, 2013). At birth, infants uses only 20% of muscles strength for motion, whilst the remaining 80% of muscles is for tension, aiding infants to maintaining a position when held, for example (Matthews, 1998). The foot of a new-born is characterised by a large amount of adipose tissue (Fritz and Mauch, 2013), which is distributed all around the foot defining the classical "fatty and rounded foot" shape, and it does not decrease until childhood (Kelikian and Sarrafian, 2011). This is accentuated also by the absence of the medial longitudinal arch (MLA) in infancy, which causes the presence of a low medial arch profile. In typically developed feet, the MLA is formed by articulation of the calcaneus, talus, navicular, the three cuneiforms, and the first, second and third metatarsals. These bones are yet to be ossified during infancy, when also the presence of a large amount of adipose tissue has been reported in site of the MLA to protect the overlying sensitive bones and cartilage structures and mitigate the excessive forces applied to the plantar surface of the foot during movements (Bertsch et al., 2004). As for the overall lower limb and foot, it is reasonable to say that development of the MLA depends on both genetic and environmental factors, but is mostly controversial, as different theories as well as methods to measure its development have been reported. For example, Tax (1985) stated that as the adipose tissue decreased between two to four years of age, the MLA would become visible. However, the typical low arch profile of the infant foot is also due to the high joint laxity, foot flexibility, and underdeveloped foot structures, which cause the MLA to collapse under walking conditions (Kirby and Green, 1992). Accordingly, Bernhardt (1988) reported that the low foot arch profile in weight bearing conditions is due to the excessive medial foot loading in infancy, which prevent the typical appearance of the MLA. This could be the reason why Bertsch et al. (2004) reported that MLA formation occurs up to six to seven years of age, when also the foot starts to demonstrate typical functional patterns during walking (Bosch et al., 2010). After the age of seven, it has been argued that minor changes in the MLA occurs, with Mauch et al. (2008) reporting that the arch is subject little maturation also up to 12-13 years of age.

Whilst structures of the foot undergo substantial changes, changes with foot dimensional changes also occur. With respect to foot length, the foot is approximately 1/3rd of its total length at birth (Maier and Killmann, 2003), with major growth taking place during the first three years of life. Accordingly, until the age of three years, feet grow in length at a rate of 2 mm per month, reaching 2/3rd of the total foot length by the age of three (Maier and Killmann, 2003, Volpon, 1994). Between the three to five years of age, the foot length increases about one mm per month, and drop to 0.8/1 cm a year between the five and 12 years of age. Increasing foot length stops in boys and girls at the age of 15 and 13, respectively (Anderson et al., 1956, Cheng et al., 1997, Gould et al., 1990, Maier and Killmann, 2003, Walther et al., 2005). Alongside length, changes in foot width also represent an important aspect of foot maturation. Studies have assessed foot width by using different measures such as absolute rear-foot (Delgado-Abellán et al., 2014, Kouchi, 1998, Sacco et al., 2015) or absolute and relative forefoot width (Jimenez-Ormeno et al., 2013, Muller et al., 2012b). Rear-foot width increases by 6.7 mm between the age of three and seven years (Sacco et al., 2015), with different maturation rates between European and Japanese and Brazilian children, who showed quicker rear-foot growth up to the age of seven years (Kouchi et al., 1998; Sacco et al., 2015). Absolute forefoot width does not change as much as foot length during infancy and childhood (Muller et al., 2012a). Furthermore, Muller et al. (2012) showed that during the first eight years of life, the forefoot is wider compared to children aged between nine and 13 years, who present slenderer feet. This is supported by measures of relative forefoot width, which decreases by 8% in proportion of foot length up to 13 years of age. If relative forefoot width shows that the forefoot decreases in proportion to foot length, absolute forefoot width shows an increase. Specifically, up to the age of eight years, Muller et al. (2012a) found that there was an increment of approximately two cm in absolute forefoot width, with an additional increase of one cm between eight to 12 years (Muller et al., 2012a). These findings were in agreement with those proposed by Jimenez-Ormeno et al. (2013), who showed that between six and seven years, forefoot width increases by 1.8 mm per year.

2.1.3.2 The influence of loading on foot development

As anticipated in section 2.1, the development of the foot is dependent upon genetic and environmental factors. Therefore, foot development is multifactorial and has to be considered not only in relation to internal influences part of the genetic program, but also in the adaptations to external stimuli from interaction with the environment (Fritz and Mauch, 2013). The influence of the repetitive loading on foot development is postulated by physiological laws that explain changes present within bony and soft tissues, namely Wolff's law (èOzkaya and Nordin, 1991) and Davis's law (Goel and Watt, 2002). With respect to Wolff's law, Ozkaya and Nordin (1991) suggest that in response to mechanical demands, bones are able to change shape, mechanical behaviour and properties. With Davis's law on the other hand, Goel and Watt (2001) referred to the soft tissue remodelling, which elongate by adding new biological material in response to unremitting tensions (Carlstedt, 1989).

Accordingly, vertical forces acting within the foot and lower limb during attainment of weight bearing developmental milestones, such as pull to stand or walking, enhance ossification and remodelling of foot bones and soft tissues structures as cells differentiation activates in response to the mechanical elastic deformation the tissues are subject to (Frost, 1994). The deformation of bones and soft tissues is caused by generation of peak forces deriving from internal (muscles and tendon increasing activities) and external forces (ground reaction force) (Jee, 1999). In vivo studies reported that repetitive strains experienced during movement bring about stress within soft and bony tissues (Lanyon and Smith, 1970). These microscopic stresses are expressed as micro lesions within the tissues and are detected and repaired by bones and soft tissue specialised units (e.g., osteocytes, osteoblasts, and osteoclasts), which lead to increasing number of cells within these tissues (Verborgt et al., 2000). In the case of bones, for example, this process has been referred to as bone remodelling, and it has been stated to be particularly important to maintain the homeostasis of calcium (Gallagher, 1991). Therefore, as infants learn and perform their own motor tasks, the progressive loads applied within the foot trigger development of healthy anatomical structures, according to Wolff and Davis's laws, thereby causing reinforcement of soft tissues, increasing robustness in the bones and tightening tendon and ligaments. Thus, addressing the effects of repetitive vertical loading in relation to the establishment of weight bearing motor tasks might be important as it might combine knowledge of typical foot function and structure changes that would enable to provide a more comprehensive view of the overall development of the foot, underpinning research and clinical practices.

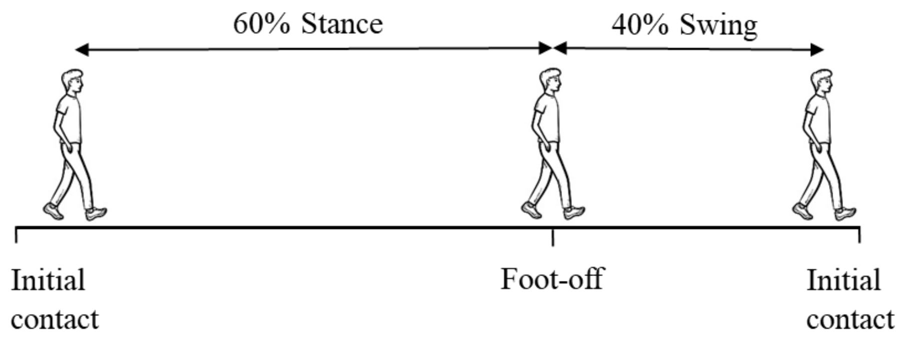
2.1.4 Paediatric gait

During infancy, the establishment of independent walking is considered one of the major motor achievements as infants finally become capable of exploring the surrounding environments without aids and support in a bipedal upright position (Adolph and Franchak, 2017, Hallemans et al., 2005). To understand the development of infant gait however, it is necessary to describe first the concepts and terminology in relation to gait analysis in mature walking, which will be reported hereafter.

2.1.4.1 Concepts and terminology of gait analysis

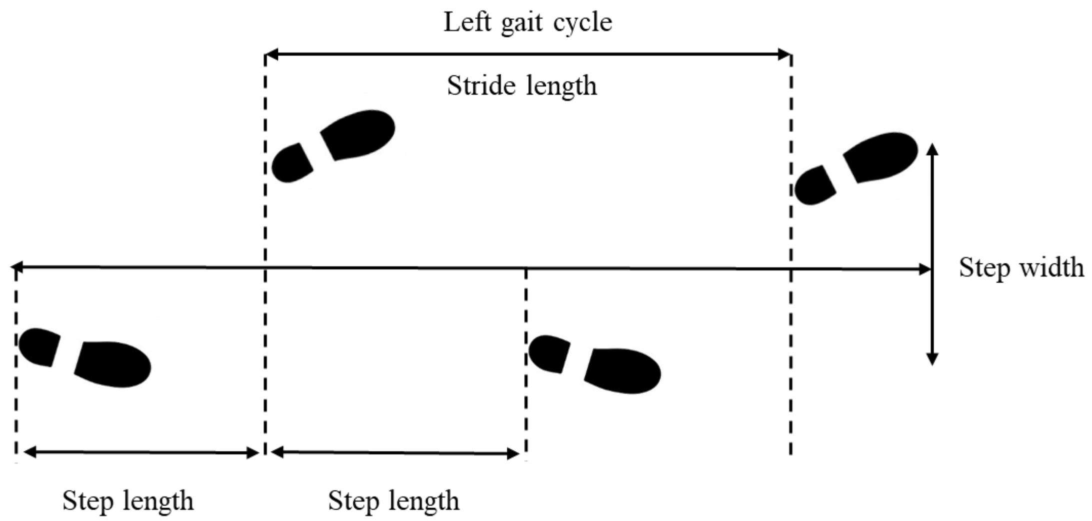
Walking is a cyclic event involving movement in the three planes: sagittal, frontal and transverse (Whittle, 2007). During gait, two main phases can be identified: stance phase and the swing phase (Stergiou, 2020). The stance phase defines the moment when the foot is in contact with the ground, while the swing phase can be described as the moment when the foot is not in contact with ground as it is swung forward (Stergiou, 2020). The stance and the swing phases are temporal descriptors of gait and occupy 60 and 40% of the gait cycle, respectively (Figure 1).

Figure 1. Main phases of the gait cycle.



Apart from the temporal aspects mentioned above, spatial parameters of gait also can be described such as: step length, stride length and step width (Figure 2). Step length is the longitudinal distance between the points of initial contact of left and right feet. Stride length defines the distances between the consecutive placement of the same feet in the anterior-posterior direction, whilst step width is the distance between left and right feet in the medio-lateral direction, measured when both feet are in contact with the ground (Hallemans, 2005). When both spatial-temporal parameters are known, cadence (number of steps taken per minute) and walking speed (speed at which certain distance is covered by the whole body during walking in a given time) can also be calculated (Whittle, 2007, pp. 56).

Figure 2. Spatial parameters of gait.



Stance phase and swing phase are both characterised by several sub-phases. Within the stance phase, four phases can be identified: loading response, mid-stance, terminal stance and pre-swing. In the swing phase, three phases are present: initial swing, mid-swing and terminal swing (Whittle et al., 2007). During stance, when the left foot is in contact with the ground at toe off and the right initial contact occur, there is a period of double support phase, also referred to as double limb stance. During swing, when either the left or the right foot are in contact with the ground, two single support phases can be defined such as the right or left single support, also known as single limb stance.

As gait initiates, there is a period of weight acceptance (Stergiou, 2020). As the weight is accepted, the limb stabilises, the shock originating from foot-ground interaction is absorbed and forward progression of the body takes place. The phase of weight acceptance is composed of initial contact and loading response. Initial contact account for only the 3% of the total gait cycle and it is usually performed with the heel, describing the initial heel contact. As the heel contacts the ground, the weight is transferred to the whole foot, defining the first rocker of the gait cycle (Whittle, 2007). After initial heel strike, loading response phase occur and consists of 3-12% of the gait cycle. During this phase, the hip begins to extend, the knee is flexed slightly to absorb the shock as whole-foot contact is made, which also stabilises the moment of single limb support, whilst the ankle is in plantar flexion (Perry and Davids, 1992).

When single limb support takes place, the body progresses forward over the foot. Within the single limb support phase, mid-stance also occurs and it accounts for 12-31% of the gait cycle. During mid-stance, a forward rotation of the shank over the foot is observed, which defines the second rocker of the gait cycle (Whittle, 2007). After mid-stance, the terminal stance phase accounts for 31-50% of the gait cycle. In this phase, the centre of mass shits ahead of the supporting foot and the heel of the supporting limb raises from the ground, defining the third rocker of the gait cycle. In this phase, hips and knees are extended, the ankle is in dorsiflexion and the foot is increasingly supinated (Perry and Davids, 1992).

The last phase of the gait cycle is the swing phase. During initial swing, the hip, knee, and ankle are in a flexed position, to enhance forward progression of the limb and promote foot clearance of the ground (Perry and Davids, 1992). Mid-swing is 75-87% of the gait cycle, when limb progression carries on, the knee is fully flexed. The swing phase ends with the terminal swing phase, accounting for 87-100% of the cycle; during terminal swing, the tibia is vertical and the hip flexed, to allow the placement of the foot for initial contact and start the next gait cycle (Perry and Davids, 1992).

2.1.4.2 Gait development in infancy and childhood

The gait of infants and children differ substantially from the mature gait reported above. Throughout the paediatric age, researchers identified two different stages of development (Thelen, 1995): the first covers the span of time between three to six months after the establishment of independent walking and describes a period of rapid development and considerable changes in spatial-temporal values. Following this, a second phase occur when slower and lesser changes take place. Within the very first months of independent walking, infants show lack of balance, postural control and muscles strength, as the neuromuscular-skeletal system is developing (section 2.1.1). For these reasons, the onset of walking is characterised by several biomechanical aspects (Winter, 2005, Sutherland et al., 1980, Hallemans et al., 2005)

- A wide base of support
- Large stance width;
- Guard position of the arms, with the arms in abduction and external rotation and the elbows flexed;
- Absence of initial contact with the heel;
- Flexion of hips and reduced flexion of the knees in both stance and swing phase;
- Prevalence of ankle plantar-flexion during stance and reduce ankle dorsiflexion during swing;

Analysis of spatial-temporal aspects of gait also found that early walking demonstrates short step length (0.12 m), a low speed (0.24 m/s^{-1}) and a quick cadence (180 steps/minute) (Chang et al., 2006, Badaly and Adolph, 2008). Accordingly, the stance phase is long and occupies the majority of the gait cycle, while swing phase is short (Clark et al., 1990). Furthermore, Sutherland et al. (1980) in their analysis of 186 infants and children aged between one and seven years, found that as walking experience increases, step length and cadence become longer and walking speed increases. The present data is however captured in laboratory-style environment, where infants were encouraged to walk in specific directions as opposed to walk freely and undirected. Studies carried out in home-style environment are less likely to alter the natural walking patterns in infancy, hence allow to capture motor behaviour that closely resemble those performed during infants' daily activities (Price et al., 2018a). Furthermore, it has been argued that the points of initiation and termination of gait are arbitrary and infants manifest different walking trajectories in a single session (Adolph et al., 2018), which are not only made in straight lines. If data of infants' gait is captured in less controlled environment, this could cause identifying also its higher variability, as the motor tasks performed would be uncontrolled. For example, studies quantifying intra-individual variability in natural environment demonstrated that step length is more variable than step width during the first months of walking, but as walking experience increases, this trend reverses and become similar to adults (Looper and Chandler, 2013, Bisi and Stagni, 2015). Nevertheless, Badaly and Adolph (2008) found that ranges of relative step length was 0.31 – 1.9 for 164 infants, which suggest that high data variability during infants' gait is an inherent characteristic of development. The development of stability and postural control has been argued to cause improvement in gait (section 2.1.2). This is in agreement with the work from Ivanenko et al. (2005). Accordingly, their work demonstrated that by comparing infants (12-15 months of age) walking with and without hand support, an increased in stability and postural control was evident considering improvement in kinematic parameters such as significant increasing walking speed, decreasing number of falls, reduced step variability and trunk oscillations in the first group. Nevertheless, when this procedure was applied to older children (2-7 years of age), Ivanenko and colleagues (2005) demonstrated the absence of changes in the aforementioned kinematic parameters, suggesting that in older children, kinematic does not depends upon increasing postural stability. Changes in trunk oscillations were also demonstrated by Assaiante et al. (2000), who found that trunk oscillations in the frontal and sagittal planes show a reduction after four months of walking experience, suggesting the presence of a more controlled gait. The presence of large trunk oscillations were reported to be the consequence of the different walking strategies identified by McCollum et al. (1995). Accordingly, during the establishment of independent walking, infants can be defined as:

- Twisters, if they twist the trunk to progress forward;
- Fallers, if they use the gravity to progress the centre of mass forward;
- Steppers, if they control foot progression to stabilise and move forward the centre of mass;

Alongside the work of McCollum et al. (1995), Bisi and Stagni (2004) identified another walking strategies adopted after one month of independent walking, which they referred to as pendulum. Specifically, the authors placed inertial sensors on the lower back and leg of infants and identified the presence of features of the trunk 3-dimensional acceleration pattern. Accordingly, the presence of pendulum walkers was confirmed as this pattern identifies the body vaulting over the leg, raising and dropping the centre of mass as propelling forward. This is reported to occur up to six months from the establishment of independent walking (Bisi and Stagni, 2005). After three to five months of walking experience however, the gait cycle is already organised in a more mature way, with an increasing knee flexion, hip extensions, ankle dorsiflexion (Sutherland et al., 1980, Hallemans et al., 2005, Hallemans et al., 2006a), as well as a greater ankle eversion moment present by the age of two years (Samson et al., 2011). By the three years of age, step and stride length resemble those in adults (Clark et al., 1990) and children are able to minimise energy dispersion during walking by controlling vertical body excursion (Winter, 2005). The work of Samson et al. (2011) also showed that up to the four years of age, metatarsal-phalangeal joints and ankle eversion moment reduces as the ankle start assume an inverted position. These characteristics supports the gradual appearance of mature-like gait, although variations have been reported up to the six years of age (Payne and Isaacs, 2016). Sutherland et al. (1980) reports that scarce development in gait occurs after the seven years of age. Ganley and Powers (2005) also agreed, reporting that by seven years of age, gait patterns of children were similar to adults for the majority of kinematic variables analysed such as joint motion of the hip, knee and ankle. However, children utilised significantly greater cadence and shorter step length, with reduced peak plantar flexor moments and diminished peak power absorption and generation at the ankle during terminal phase of stance (Ganley and Powers, 2005). Peak plantar flexion moments during late stance in the hip, knee and ankle resemble adults’ patterns in children older than nine years, who also showed higher peak power generation than children younger than nine (Chester et al., 2006). Accordingly, a later observation reported that immature gait patterns are still present in late childhood and adolescence due to performance of adult-like speeds with however shorter leg (Froehle et al., 2013). In addition, it has been showed that values of base of support, single and double support time develop around the age of 14 and 18 in females and males, respectively, (Froehle et al., 2013), with decreasing variability in gait speed recorded into adolescence (Müller et al., 2013). Therefore, it is possible to state that resemblances of typically developed gait patterns are increasingly visible as age increase and infants and children continue to develop new walking skills and strategies, which is supported by continuous changes in lower limb kinematics up to adolescence.

2.2 Quantifying foot biomechanics in paediatrics

During the development of typical gait, the biomechanics of the different anatomical segment of the body and more specifically of the lower limb, such as the knee or the foot, undergoes major functional changes that can be analysed through biomechanical principles and analyses. The continuous advancement of technology has led to development of important tools and resources to enhance evaluation of foot biomechanics. Kinematic and plantar pressure analyses constitute a large part of approaches used over the years to study and quantify foot function characteristics and changes in paediatrics (Dominici et al., 2007, Hallemans et al., 2003, Hennig and Rosenbaum, 1991, Mesquita et al., 2019, Samson et al., 2011, Bisi and Stagni, 2015, Bosch et al., 2010, Dulai et al., 2021). In the thesis however, kinematic data will not be investigated and therefore, only introductory concepts of plantar pressure analysis will be reported (section 2.2.1), alongside a critique review of the different approaches to plantar pressure data collection (section 2.2.2) and analysis (section 2.2.3). By exploring these sections, strengths and limitations of the plantar pressure approaches in infancy and childhood have been highlighted, providing directions for future research applications.

2.2.1 Introductory concepts of plantar pressure

Pressure is a perpendicular vector acting on the surface of an object (e.g. the foot), expressed in kilo-Pascal (kPa) and calculated as the ratio between the force (F) and the area of contact (A), according to:

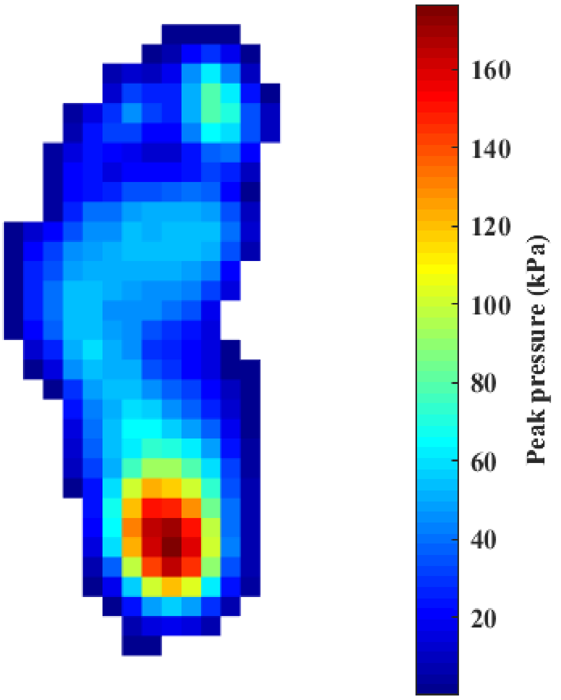
$$P = \frac{F}{A}$$

Equation 1. Pressure calculation.

Plantar pressure is defined as 2D quantity, as its calculation is based on two spatial dimensions (x, y), defining the plantar surface of the foot, where the acting forces are captured. Pressure is also smooth in its spatial dimension and characterised by distinct structural bounds (foot surface) (Pataky, 2010). Analysis of pressure generates a sequence of frames, which correspond to the pressure images obtained between the initial contact and phase and the moment the foot leaves the ground, which define the stance phase. Throughout the stance phase, sequences of frames are collected (generally at 50 or 100 Hz) and for each sensor within the pressure platform, a value of pressure is stored and visualised (pixel)

(Pataky and Maiwald, 2011). During the stance phase, the total number of pixels loaded and resulting in non-zero values generates a maximum pressure picture (MPP). Intensity of pressure is represented generally by a colour scale, with shades of blue to represent low-pressure areas that change into yellow to red shades as pressure increases (Figure 3).

Figure 3. Example of intensity of peak pressure by colours. Shades of blues represent low-pressure areas, which change in yellow to dark red when pressure intensify.



The measurement of pressure is obtained using transducers, also referred to as pressure sensors, that are able to quantify the perpendicular effects of a force vector acting on a surface (Giacomozzi, 2010). In general, two of the most commonly used sensor technologies within these systems are resistive and capacitive. Overall, these sensors provide an electrical voltage that can be considered proportional to the pressure applied to the sensors (Razak et al., 2012). However, some key differences are present between the two sensor technologies, which have been highlighted in the following section, alongside the key factors to consider in the choice of pressure measurement technologies to collect paediatric plantar pressure data.

2.2.2 Plantar pressure data collection

In the 20th century, various equipment started to be used to explore plantar pressures, such as ink-based sheets, but plantar pressure technologies have been introduced later on (Soames, 1985). As technology advanced, novel sensors and systems to plantar pressure data capture have been developed, which were reported and described in the following sections.

2.2.2.1 Overview of plantar pressure sensors and systems

1. *Pressure sensors*

Pressure sensors are much studied in the literature for their inherent design features that allow estimating pressure-related aspects of certain motor tasks. The two main types of pressure sensors technologies are resistive and capacitive, which are composed of different materials and capture pressure information following different principles.

Resistive sensor technologies are composed of a conductive polymer, placed between two electrodes (Razah et al., 2012). The conductive polymer varies its resistance following application of pressure to its surface, causing the contact of conductive particles that augment the flow of current within the sensor (Razah et al., 2012). As a result, the electrical signal flow generated by pressure deforms the conductive layers that form the sensor, which signal intensity rely on the amount of pressure applied against the sensors. For this reason, resistive sensors are deformed over time, as pressure deforms the sensors, tend to lose sensitivity due to the continuous use, and need frequent calibration (Aqueveque et al., 2018).

As opposed to resistive sensors, capacitive sensors are made of two conductive plates, with a dielectric material in between. When pressure is applied onto this sensor, the dielectric material bends and the distances between the two conductive plates is modified, therefore varying the sensors capacitance, which responds to the different amount of pressure applied within each sensor (Razah et al., 2012).

Both resistive and capacitive sensors can be arranged as individual or matrix sensors. Individual sensors are generally small and placed in specific areas of the foot (e.g. metatarsal heads), to provide information of the pressure in that precise region (Branthwaite et al., 2013). These sensors are cheap and the demanding associated with computer processing power is lower (Richards, 2018). Their use is also particularly valuable in case of analysis of feet with deformities, allowing a specific pressure detection and preventing, for example, capturing data set originating from atypical foot placements onto the ground. Pressure technologies using individual sensors, such as FlexiForce sensor (Tekscan, USA) and the WalkinSense (Kinematix, Portugal), generally need to attach them onto the landmarks of plantar surface of the foot, for which accurate identification is needed to provide correct plantar pressure information. As a result, the same challenges occurring with marker placement in kinematics might occur, especially in the context of infants and children plantar pressure analysis.

As opposed to individual sensors, matrix sensors are arranged as multiple arrays of single sensors forming pressure platforms and in-shoe pressure systems, which are the main pressure measurement devices in commerce nowadays. Specifically, cases of matrix resistive sensors technologies are the MatScan® platform systems (Tekscan, USA) and F-Scan® in-shoe pressure systems (Tekscan, USA). Examples of matrix capacitive sensor technologies are the EMED® platform systems (Novel, Germany) and Pedar® in-shoe pressure systems (Novel, Germany). The use of these systems depends on the research question and the type of device used to capture plantar pressure information.

2. *Plantar pressure systems*

Pressure platforms can be adopted for both static and dynamic evaluations, and can be used for barefoot walking, thereby removing the applications of wires that could influence a natural gait pattern and removing the impact of footwear. The first aspect is particularly useful in the context of paediatric data collection, as research in infancy have highlighted the importance of collecting biomechanical data in a friendlier environment to avoid capturing unrealistic patterns of walking (Adolph et al., 2018, Price et al., 2018a, Price et al., 2018b). Furthermore, pressure platforms can be found in different sizes (e.g. in the form of walkways), so that constraints related to the short walking paths are relatively overcome. In fact, platforms with a measuring surface large enough to allow acquisition of at least a full stride should be preferred for plantar pressure analysis. Nevertheless, platform pressure systems tend to be more cumbersome and require to be positioned in large spaces to allow the users to take a sufficient number of trials during acquisition of the data to avoid participants targeting the platform area.

In-shoe pressure systems are portable, characterised by lightweight and flexible sensors, which allow them to be adjusted to shoes, enabling to capture data on different surfaces and becoming more suitable to assess interaction of the foot with footwear, for example. Furthermore, in-shoe devices are characterised by a low power consumption as they would not have a direct connection with the electric power and should allow for a long data acquisition. However, in-shoe pressure systems could have wires or data boxes attached to power the batteries as well as slippery surface that could influence normal gait patterns. The presence of wires and boxes might be not tolerable by infants and children, who could touch the equipment and cause signal disruptions. In addition, it has been showed that in shoe-pressure systems tend to capture lower average peak pressure within the heel, midfoot and forefoot as the interactions between the foot and the shoe mask high pressure (Chevalier et al., 2010). Therefore, it is important to consider characteristics of these systems before collecting data, in order to target the approach to data acquisition for the specific purposes and sample of interest.

2.2.2.2 Specifications of sensors' technologies

The specifications of the pressure measurement technologies, whether they are in the form of plantar pressure platforms or in-shoe systems, are important when data collection in infancy and childhood is undertaken. Specifically, in the field of paediatric plantar pressure data collection, several factors are important to consider related to sensor performance, such as: (i) the system's spatial resolution (ii) the sampling frequency and (iii) the sensitivity of the sensor within the pressure system used.

(i) The number of sensor per square centimetre defines the spatial resolution of a pressure system, which is essential to consider in the acquisition of accurate plantar pressure data in infancy and childhood. For example, when the foot of a walking infant is considered, a system with a reduced spatial resolution (e.g., 2 sensor per cm^2) could not capture the true area of the foot in contact with the ground, as the foot is small. In this case, the real pressure distribution would be different from the captured pattern as it would be reduced to a smaller area, hence the real pattern would be missed and pressure could be underestimated. This highlights that to capture plantar pressure and contact pattern of small feet, spatial resolution per square centimetre should be high (e.g., 4 sensors per cm^2) (Bertsch et al., 2004; Bosch et al., 2010). For similar reasons, the threshold for sensors activation is also an important aspect to consider when assessing plantar pressures of infants and children.

(ii) As for section 2.2.1.1, the sampling frequency is also very important during plantar pressure analysis as it defines the number of times a sensor is activated per second. Accordingly, a low sampling frequency would not be able to measure how quickly the sensors can respond to the changes in pressure, for example during running, walking at higher speeds or if erratic gait patterns are present, such as in infancy (Adolph et al., 2018). This could affect those pressure variables that include a time component, such as peak pressure, resulting in missing data for that variable. Plantar pressure systems normally collected walking data with a 50–100 Hz sampling frequency, which is considered acceptable (Richards, 2018). However, deciding the correct sampling frequency depends also on the motor tasks the sample perform. Activities performed at higher speed, such as adult running, would require a higher sampling frequency compared to walking. For example, it has been reported that minimum sampling frequency of 200 Hz is necessary, in order to capture the activation of the sensors in a reduced time frame (Razak et al., 2012).

(iii) Another aspect to consider during acquisition of plantar pressure data in paediatrics is the sensitivity of the sensors. Given the characteristics of the sensors reported in the previous section, it is possible to say that resistive sensors are less sensitive (e.g. pressure ranges 20 – 600 kPa) than the capacitive (e.g., pressure ranges 10 – 1270 kPa) as a higher load is necessary to activate the sensors. Low sensors sensitivity (such as resistive) would lead to capture less pressure patterns information, as infants' weight is lower than adults, hence the amount of pressure applied to the sensor is lower. For example, repeatability of pressure measurement was investigated using a technology system based on both resistive sensors (Tekscan) (Cousins et al., 2012) and capacitive sensors (Novel EMED) (Tong and Kong, 2013) in children aged between seven and 11 years and six and 12 years, respectively. Cousins et al. (2012) found that within and between-sessions repeatability was good for all the regions except for the lateral toes 2-5, where repeatability results were moderate. On the contrary, Tong and Kong (2013) found good to excellent repeatability values for lateral toes 2-5. Differences between the two studies are likely present in terms of testing protocol and sample, for example, and thus considerations need to be made with care. Nevertheless, it is important to highlight that systems differed in terms of sensors sensitivity as well as in the resolution and frequency. Therefore, it can be assumed that these factors might lead to less accurate identification of small regions, leading to missing pressure information.

2.2.2.3 Novel EMED technology

The above section highlighted that the specific characteristics of the sensors have to be taken into careful considerations for pressure data acquisition, as different technologies can have considerable impacts on generating pressure data. Among the various pressure systems available in commerce (F-scan, Tekscan, Zebris, Matscan, Pedar etc.), the Novel EMED plantar pressure hardware is the most commonly used technology to study static and dynamic plantar pressure patterns (Putti et al., 2008). Repeatability and accuracy results however cannot be directly compared between studies if data is captured by different technologies (e.g., Tekscan and Novel EMED). This means that repeatability can be a function of the hardware used, the sample analysed as well as dependent to the operator. Therefore, in the following paragraphs, accuracy and repeatability values will be reported only for the use of the EMED hardware, which is the hardware that is going to be used within this thesis for plantar pressure data acquisition and generation.

As previously mentioned, the novel EMED hardware uses capacitive sensors, and repeatability as well as accuracy of plantar pressure measurement have been demonstrated in adults (Akins et al., 2012, Gurney et al., 2008, Hughes et al., 1991, Putti et al., 2008) and children (Tong and Kong, 2013). Based on adults' pressure and forces values, EMED generally showed an accuracy of ±5%, with error rate between-day set at 16.9% (Putti et al., 2008) and at less than 5% for each trial collected (Hughes et al., 1991). Interclass correlation coefficient (ICC) for EMED was also lower than 10% for peak pressure, contact area, contact time, force-time integral, and pressure-time integral and instant of peak pressure in comparison with other systems (Putti et al., 2008). This is in accordance with a previous study (Hughes et al., 1991), which also demonstrated that the excellent repeatability (ICC> 0.90) for the measurement of force, area and pressure depended also on number of pressure trials collected. As opposed to these studies evaluating repeatability of EMED by analysing pressure variables, Atkins et al. (2012) also verified the test- retest repeatability of EMED identifying 15 geometric parameters (e.g., foot length, width, heel width, forefoot, heel and hallux angle etc.). All 15 measures were proven to be reliable (ICC>0.8) with 12 measures reaching ICC>0.9.

Repeatability of plantar pressure parameters using EMED was also investigated in a sample of 21 children between six and 12 years of age (Tong and Kong, 2013). Authors reported an overall good-to-excellent ICC, with values ranging between 0.61 and 0.98 (Tong and Kong, 2013). Despite this work, the majority of the existing data for the use of EMED hardware were produced on adults' walking trials. Given the dependency of pressure measurements to the sample analysed, and considering the scarce presence of data regarding repeatability of the EMED hardware for pressure data acquisition in infants and children, it is unclear whether EMED can be adopted to identify pressure patterns in infants and children reliably. As a result, considerations relating to the repeatable use of EMED in infancy and childhood have to be cautious and further and targeted studies are needed to test repeatability of pressure measurement devices on walking trials of infants and children using the Novel EMED technology.

2.2.3 Plantar pressure data analysis approaches

As presented previously in section 2.2.1, the aggregation of loaded pixels forms a maximum pressure picture (MPP), defined as a maximum digital pressure image containing specific pressure information. MPPs of walking trials can be also referred to as "pressure steps". Once the MPPs are generated, researchers and clinicians are able to describe the interaction that occur between the plantar surface of the foot and the ground. Therefore, plantar pressure provides quantitative data about the biomechanical characteristics of the foot (Rosenbaum and Becker, 1997), capturing foot-grounds interactions during performance of different weight bearing tasks such as walking or running. To examine foot function however, plantar pressure data collection requires further stages of data processing, which involves the use of different approaches for data generation and analysis. In the following sections, the variety of approaches to pressure data adopted by the research community was evaluated, in order to provide an overview of the most common adopted pressure analysis approaches and to highlight potential strengths, limitations and gaps in the knowledge within the field.

2.2.3.1 Introduction to masking analysis

The most common approach to analysis and interpretation of pressure data is to identify on the plantar surface of the foot the presence of regions of interest (ROIs), which correspond to specific foot anatomical areas (Deschamps et al., 2009), such as the heel, the mid-foot and forefoot. The aggregation of multiple ROIs define a mask. This approach is referred to as masking analysis (Rosenbaum and Becker, 1997). Masking analysis enables researchers to capture information about the characteristics of each ROI, where different pressure variables can be extracted and analysed further, such as: peak pressure (kPa), contact time (ms), contact area (cm^2), maximum force (N), force-time integral ($N*s^{-1}$), and pressure-time integral ($kPa*s^{-1}$), and centre of pressure (COP) trajectories. Definitions of the aforementioned variables have been reported in the thesis glossary.

In paediatrics, plantar pressure variables have been extracted and analysed for a series of different aims, such as:

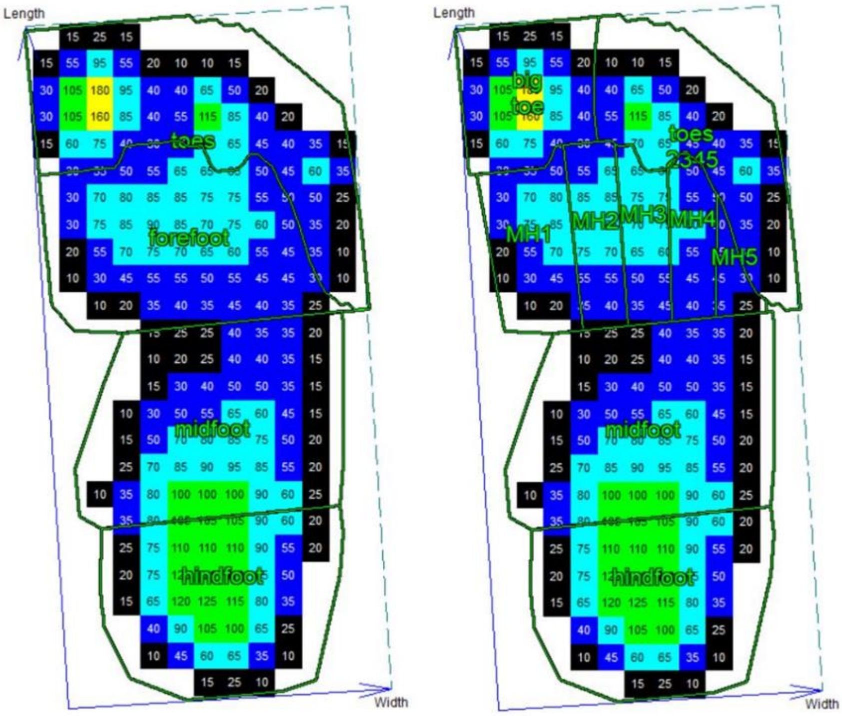
- Evaluation of functional deficits in children affected by juvenile idiopathic arthritis (Merker et al., 2018);
- Assessment of musculoskeletal foot conditions associated with neurological disorders (Look et al., 2021);
- Investigation of the typical development of foot biomechanics (Bertsch et al., 2004; Dulai et al., 2021);

As a general rule of thumb, the use of multiple ROIs is considered more appropriate compared to the examination of the foot as whole (Stebbins et al., 2005). Accordingly, it constitutes a more specific examination of the pressure and forces acting on different areas of the plantar surface during weight bearing activities such as walking or running (Hayafune et al., 1999).

2.2.3.2 Regions of interest selection

The choice of the number of ROIs is arbitrary, as the research question generally informs the choice of ROIs in terms of number as well as their definition. For this reason, there is currently no consensus on optimal ROIs selection in both adults and paediatric plantar pressure studies. For example, in order to investigate pressure patterns of an at-risk diabetic populations, four ROIs have been defined (heel, first and second metatarsal heads and hallux) (Lung et al., 2016), while to study typical pressure patterns of infants and children, studies adopted different numbers of ROIs. For example, a five-region mask has been the most common approach to explore typical plantar pressures throughout the paediatric age (heel, midfoot, forefoot, hallux, toes) (Bertsch et al., 2004; Bosch et al., 2010, Phethean et al., 2014; Mesquita et al., 2018). Nonetheless, other studies looking at plantar pressures of typically developed infants and children divided the foot in three regions (Muller et al., 2012), seven regions (Hennig and Rosenbaum, 1991; Hennig et al., 1994), or nine regions (Kellis, 2001, Phethean et al., 2014) (Figure 4).

Figure 4. Example of four region of interests (ROI) mask (left) and nine ROIs mask (right). Data reported from the analysis of infants in this thesis.



2.2.3.3 Types of masking approaches

Once the amount of ROIs are selected, three main types of masking approaches can be used to create and apply the masks to the MPPs. Mask application can occur in the form of i) manual masking ii) standard automatic masking and iii) customised automatic masking (Stebbins et al., 2005).

i. Manual masking

Manual masking defines a full operator-dependent approach, where users manually create and apply the ROIs (e.g., heel, midfoot, forefoot etc.) to each individual MPPs. Studies establishing accuracy and repeatability of manual regional analysis in the paediatric field are scarce. Cousins et al. (2012) found that in a group of children aged between seven and 11 years, repeatability of their manual approach was good both within and between sessions for all the regions and variables analysed except for the lateral toes 2-5. Specifically, the authors reported that in this area the coefficient of variation was the greatest for both peak pressure (27.15 kPa), peak force (41.67 N), force-time integral (48.31 $N*s^{-1}$) and pressure time integral (56.08 kPa*s^{-1}). Repeatability of manual masking have been proven also for adults' pressure data. Accordingly, intra and inter observer repeatability studies have been undertaken in an adult population affected by forefoot deformities (Deschamps et al., 2009). Based on a sample of 10 adults, the authors showed a good intra-observer repeatability and an overall good inter-observer repeatability across the five metatarsals, although moderate and poor ICC values were identified for the second (0.77), the fourth (0.75) and the fifth metatarsals (0.54) respectively.

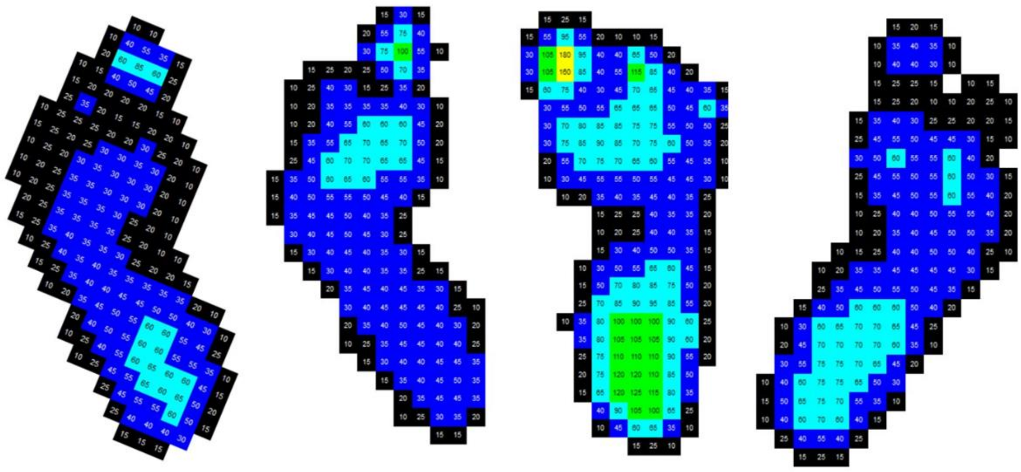
Despite the good to excellent repeatability results, it is reasonable to say that the major obstacles of the manual approach are its limitations in objectivity, as manual masking relies on the ability, knowledge and consistency of the researchers to identify the ROIs and apply the mask to the MPPs. In other words, a researcher can demonstrate high intra-rater repeatability and accuracy in dividing the MPPs, but different researchers would have different experience, different interpretation or different knowledge of the pressure data, resulting in possible low inter-raters repeatability and/or accuracy. Moreover, when a large amount of pressure data need to be processed, a full manual approach would be limited in application as the more pressure data are processed manually, the larger the error in the subjective identification of the ROIs. This is again due to inherent dependency of the approach to the operator. Therefore, it is reasonable to assume that manual masking approach can find an appropriate application for processing of small data sets that would be difficult to examine in other ways (e.g. highly deformed feet or irregularly shaped). Additionally, it can be adopted for example, during every day clinical practice or for case study purposes as its applicability mainly concern the amount of pressure in a particular region where treatment needs to be applied.

ii. Standard automatic masking

The standard automatic approach is the most common within the broad masking analysis field, as it is a standardised, repeatable approach (Putti et al., 2008), enabling straightforward data handling and efficient batch processing of research pressure data. With this approach, ROIs are identified by the software and the mask is applied automatically (Liu et al., 2005). Specifically, standard masking analysis can occur according to algorithms created for different automatic identifications of ROIs. For example, division of the foot in ROIs by using geometric foot measurements has also been undertaken and it can be considered reliable according to Akins et al. (2012). Specifically, the authors used the standard mask to identify 15 measurements related to foot geometry of 10 adults, such as foot length, forefoot width and heel width, and demonstrated a high test-retest repeatability for all the measurements (ICC= 0.80-0.90). Automatic percent masks based have also been used in adults to identify ROIs automatically (Finestone et al., 2012, Gurney et al., 2008). With percent masks, the plantar surface of each foot is divided in areas that correspond to the percent of foot length and width, and the division is based on the longitudinal foot bisection and perpendicular lines drawn to the bisection (Finestone et al., 2012). Such approach has been reported also for the study of a two-years-old clinical population in two studies, who used percent masks to divide the foot in 10 regions (Jeans et al., 2014, Jeans and Karol, 2010). Nevertheless, the suitability of such mask in infancy has not been reported. Gurney et al. (2008) have validated the use of percent mask in a population of 10 adults. Specifically, the authors a good between-day repeatability across a ten region percent mask (lateral and medial heel, lateral and medial midfoot, lateral, central and medial forefoot, hallux, second toe and third to fifth toes), with the averaged ICC demonstrated at 0.85. However, the authors reported lower repeatability values ranged between 0.68 and 0.78 for the medial midfoot, lateral toes and lateral forefoot, arguing that the results might have been influenced by the high-pressure variation in those regions during walking. To overcome masking issues related with variable pressures, standard masks based on pressure gradients algorithms have also been used to identify ROIs. This is more precise than accounting for foot measures only, as it enables the identification of specific areas of the foot that could be difficult to identify only with foot specific length or width (e.g. metatarsal heads) due to the lack of clear anatomical landmark on the MPP. Finally, ROIs can be defined based on foot anatomy. For example, Giacomozzi and Stebbins (2017) defined the ROIs based on the anatomical foot template. More specifically, authors used kinematic markers to identify the precise anatomical landmarks of the foot, without relying on pressure gradient and/or typical foot measures (length and width). Therefore, it is possible to say that the standard masking approaches can be adapted to specific requirements as well as research questions, and thus, it can be considered highly versatile.

It can be argued however that limited performance of the standard masks could occur in certain circumstances. For example, they could find some limitations for the analysis of pressure data in young populations, which might be the reason as to why repeatability studies reporting the use of standard methodologies in paediatrics are scarce. In paediatrics, the hardware might fail to identify the ROIs, as infants and children likely present incomplete or irregular foot profiles on the pressure platforms (Figure 5), due to the ongoing development of foot and movements related to walking. Accordingly, variability in contact patterns were also reported by Price et al. (2017), who found high intra-individual differences of foot profiles captured by the pressure systems. With highly variable contact patterns, it would be also reasonable to detect high intra and inter-individual pressure variability, which can be appreciated also in figure 5. With a set of variable pressure data in terms of pressure and contact patterns, the use of standard masks need to be carefully considered due to the criteria that the software packages use to identify regions. In fact, the standard masks are based on either pressure gradients, geometric algorithms, or both, of typically developed feet and habitual contact patterns, and thus might lack the ability to define automatically incomplete or irregular pressure data (Giacomozzi and Stebbins, 2017). Therefore, these considerations highlight the presence of challenges in relation to such approaches to plantar pressure data in infancy and childhood, and that the accuracy of ROI identification might be lower in developing populations, which consequently could affect data analysis and interpretation.

Figure 5. Example of different types of foot profiles and contact patterns in walking infants.



iii. Customised automatic masking

In the presence of a heterogeneous and highly variable set of plantar pressure images, a customised-automatic masking approach could be an appropriate solution. In this case, the researcher could introduce the ROI definition based on predetermined criteria (e.g., the researcher establishes the ROI based on customised percent of foot length and width). However, the creation and application of the mask on each MPP is automatic. As a result, the customised side of the approach allows researchers to adapt the mask to pressure data highly variable in shape and dimensions, or to pressure data captured from feet with deformities. On the other hand, the automatic creation and application of the mask to each MPP defines an objective approach. This would help limit the possible regionalisation errors highlighted with the standard masks, as well as the lack of objectivity encountered when the manual masking is adopted. As an example, Wallace et al. (2021) demonstrated that the standard masking approach was more inaccurate when pressure data originating from children with unilateral clubfoot was masked compared to data captured from typically developed children. To solve this problem, they reported the use of a semi-automatic masking approach consisting in applying an automated mask and modifying its application manually to fit the data. This therefore highlighted the presence of a customised approach that would enable researchers to provide a more precise methodology that would consider specific characteristics of the sample of interest. The customisation process of ROIs identification represents therefore key point that it is important to highlight. As such, researchers would need a clear and precise justification for the choice of the criteria chosen to establish the ROIs. In adults' population, Deschamps et al. (2009) used the x-rays of the participants to enhance the customised identification of the masks. This could be, for example, an appropriate solution to establish the real percent of foot length occupied by each ROI and would be specific to the population of interest. However, this is high-cost and demanding task, which could not be undertaken easily for ethical and safeguarding issues, especially in infants and children populations. Furthermore, the performance and the accuracy of this approach to pressure data would rely on specific population characteristics, as a custom mask would be created based upon a certain sample. Thus, results for the performance of this approach would be transferable only on population with the same characteristics. This then requires researchers to establish a strong and well-defined methodological protocol to replicate the analysis between researchers or for further analysis purposes.

As general conclusion of this section, it is possible to state that each of these masking approaches have strengths and limitations in their application, especially for the analysis of particular plantar pressure images, such as those captured from infants and children. It is difficult to determine whether the repeatability results previously reported for some of the approaches could be used to validate the choice of a masking approach. Accordingly, repeatability of a specific analysis can be influenced by different factors related to studies (e.g., testing protocol, data collection, resolution and accuracy of pressure measurement devices and the number of ROIs) or to the sample characteristics (e.g., age, weight etc.). Hence, each approach should be considered in relation to their strengths and limitation when applied to specific populations (e.g., infants and children). Although the standard masking approaches are the most commonly used and largely validated (especially in adults), it is reasonable to conclude that all the approaches can be appropriate for pressure data analysis, as they are versatile, deductive and depend on the research questions and hypotheses stated by researchers, as particular populations would require a specific data approach.

2.2.3.4 Introduction to pedobarographic Statistical Parametric Mapping (pSPM)

As an alternative to masking analysis, Statistical Parametric Mapping (SPM) has been introduced for the analysis of kinematic and plantar pressure data (Pataky, 2016). SPM was initially validated to study regional blood flow in functional fMRI and PET brain images (Friston et al., 1991, Friston et al., 1994), but its flexibility allowed application also to several biomechanical fields, including the study of plantar pressure. When SPM is applied to plantar pressure data, it is referred to as pedobarographic Statistical Parametric Mapping (pSPM), or pixel-level analysis. In general, pSPM is a methodological approach for the analysis of pressure data that has been demonstrated relatively recently (Pataky and Goulermas, 2008). Application of pSPM derives from the similarities between the plantar pressure field and functional brain images. They are both smooth vector fields, defined in functional units, bounded by either their anatomy, temporal events or both (Pataky, 2010) and characterised by quantifiable spatial fields within their boundaries (Pataky, 2012).

The pressure data is smooth by nature in the spatiotemporal dimension, and thus, allow pSPM to return, within the pixels, modifications of values that are a direct consequences of the function of the unit considered (the foot) (Friston et al., 1995; Pataky and Goulermas, 2008). Pressure data in biomechanics is generally considered 2D, as it is represented by a vector field (pressure) that changes in intensity relative to its spatial characteristics (foot anatomy) (Friston et al., 2005). In the pressure field, pSPM reproduces the flow of plantar pressure in its continuous 2D pressure field, where statistical inference is conducted at each pixel. As a result, statistical significance (usually $p<0.05$) can be found directly in the anatomical location corresponding to the position of a specific pixel on the plantar surface of the foot, without regionalisation being necessary.

2.2.3.5 Comparison between pSPM and regional analysis

Masking analysis and pSPM represent the main approaches to pressure data analysis, as previously highlighted. Therefore, it is important to clarify their use within the paediatric plantar pressure field. Highlighting advantages and disadvantages of the approaches helps enhance knowledge about their application to analysis and interpretation of infants and children pressure data. As showed before, masking analysis is the most common approach in the pressure field and its application is well supported by many technologies, for which hardware includes automatic approaches for masking processing (EMED, Tekscan, Pedar etc.). Regardless of the type of masking approach chosen (manual or automatic), masking analysis is easy to implement as it has been developed to be user friendly and accessible to researchers and clinicians. A large amount of data can be also managed easily and data processing and analysis does not involve the understanding of particular statistics packages or coding languages (such as Matlab or Python). Masking analysis is, however, a hypotheses-driven approach, and a specific number of ROIs and pressure variables can be identified to answer to specific research questions. This therefore explains why plantar pressure studies using masking are diverse and heterogeneous in the approaches to data analysis, as the studies used it to testing different hypotheses. When regional approaches are adopted, statistical analysis can be conducted for each individual region or between regions, producing statistical results for the pressure variables considered (such as peak pressure or contact area). Given these considerations, exploratory and developmental studies in the paediatric field can find some limitations with its use, specifically relating to:

i. the amount of pressure information to process and analyse;
ii. the approach to statistical analysis;
iii. the consequent interpretation of pressure data;

(i) The co-dependency of masking analysis to the hypotheses implies that pressure data can be partly ignored, as researchers can choose not to investigate data entirely. For example, let us consider that pressure data is captured at 100 Hz, with a system of a sensor resolution of four sensors per cm^2. Given these system specifications, a typical foot of a walking infant of two years of age with a surface of 53 cm^2 and an average stance phase of 500 ms duration (Bertsch et al., 2004) would produce approximately 11,000 pressure values. Part of these information can be lost if data is handled by sacrificing and discarding pressure information (e.g., considering a whole foot region instead of dividing it in its medial and lateral components), thus reducing data to regionalisation techniques. In a study by Booth et al. (2019), authors compared the amount of pressure data loss on a group of 33 healthy adults with implementation of different methodologies to plantar pressure analysis (e.g. masking analysis and pSPM). They found that conventional ten-regions masking analysis using peak pressure demonstrated an information loss of 99.1% and spatial-dimensionality loss of 20.8% compared to pSPM analysis. Similarly, masking analysis using pressure-time integral retained 0.00001% of the pressure information collected by pSPM, suggesting that the use of data reduction techniques such as masking analysis should be adopted as complementary to the findings from pixel-level analyses.

(ii) Because the plantar surface of the foot is divided in regions, statistical analysis is non-continuous and undertaken separately for each region. For this reasons, regional approaches imply that the ROIs are functionally independent, while they are part of a smooth functional unit (e.g. foot) which components (e.g. heel, midfoot) are functionally related to each other during motor tasks such as walking (Pataky and Goulermas, 2008). Dividing the foot into regions therefore discretise the continuous 2D plantar pressure field, reducing spatial resolution, misleading statistical results. For example, if the aim of a study is to calculate significant differences between two conditions in the individual regions of the foot using peak pressure (representing the sensor which was loaded the most in a region), differences can be identified but without knowledge as to where they are in the real anatomical correspondence of the foot. In the case of paediatric plantar pressure analysis, using masking analysis would also retain the assumption that foot regions function already in a typical manner and that a clear anatomical definition of foot regions exists for infants and children. However, to date, there is no consensus about definition of ROIs in the paediatric sample, due to the continuous growth and developmental processes occurring throughout the paediatric age.

(iii) Adopting methodologies that lose pressure information, discretise the 2D spatial field of pressure and identify regions based on typically developed feet potentially lead to misleading interpretations of the results if applied to the paediatric sample. Furthermore, researchers adopting masking analyses would be presented with results for a certain number of variables (peak pressure, contact area, contact time, pressure-time integral etc.) and regions. According to the research questions, they would have to match findings from each variable and simultaneously integrate findings to the developing foot anatomy in order to understand pressure patterns and interpret them in relation to the foot behaviour in infancy and childhood. Because of these factors, regional analysis can be considered as a low-resolution approach to analysing pressure data, which could lead to loss of information and biased data interpretation (Deschamps et al., 2015). On the contrary, pSPM handles the data within the pixels in their real anatomical correspondences. This does not require creation of regional boundaries within the plantar surface of the feet, hence removing the issue of spatial discretisation as well as limitations related to the anatomical definition of ROIs in paediatrics. Furthermore, pSPM does not lose pressure information and it is representative of the underlying pressure field produced by the foot-ground interactions, as there are no independent regions on the plantar surface of the foot that interrupt the flow of the 2D pressure field (Pataky et al. 2013). Within an adult population, it has been showed that there are differences in outcomes produced by masking analysis and pSPM. For example, Pataky et al. (2008b) compared results from pressure analysis in a population of 10 males (mean age 28.8 years) at different walking speed using regional analysis and pSPM. The authors demonstrated that both approaches found a positive and statistically significant correlation between walking speed and peak pressure at the heel and toes. However, only pSPM highlighted that there was a negative correlation at the midfoot and proximal forefoot (both medially and laterally) between walking speed and peak pressure, as peak pressure decreased in those regions with increasing walking speed. This indicated that there was a reduced collapse of the longitudinal arch, possibly due to the active and passive structures, that prevented the arch to collapse. On the contrary, masking analysis only showed a negative correlation on the lateral side of the forefoot, leading to the assumption of a higher medial loading with increasing walking speed. Differences were due to the regional approach extracting only a single peak pressure value within the region analysed. Similarly to the above, Phethean et al. (2014) also carried out a comparison between regional analysis and pSPM in children (4-7 years of age). The authors reported that, as opposed to the regional approach, pSPM analysis demonstrated a significant negative correlation between increasing age and peak pressure at central metatarsals and the lateral border of the heel, which suggested a change in heel morphology.

Overall, these results highlight that the limitations of masking analysis are likely to lead to misinterpretation of data representing both foot function and morphological changes.

Characteristics of pSPM highlighted in this section make reasonable to say that pSPM is higher in definition and resolution compared to masking approaches. Nevertheless, pSPM has never been adopted in infancy and it has been adopted only once in childhood (Phethean et al., 2014). Thus, conclusions regarding the application and use of pSPM has to be clarified in the field of paediatric plantar pressure analysis. Moreover, analysis with pSPM might represent a challenge for its higher computational demands than masking analyses. As previously reported, the use of masks represent a user-friendly approach, hence it is easier to implement and does not require particular expertise in the field of plantar pressure image processing. On the contrary, analysis with pSPM requires phases of data processing that have to be implemented through codes in programming language (e.g., Matlab, Python), which require higher computational skills. In fact, data processing required to perform pSPM is not without challenges. A key point to consider is the approach to pressure images registration. Specifically, pSPM is performed on pressure images that have to optimally overlap onto each other, defining the registration process, which is a statistical requirement to adopt pSPM (Pataky, 2012). Registration however might not be trivial in the paediatric sample, due to the high variability of the data captured from infants and children. Specifically, on thing to be controlled is the testing protocol adopted by the studies, which could lead to capture pressure data, which might or might not be characterised by high variability. Accordingly, adopting a systematic gait protocol asking infants and children to walk in straight lines from one point of the platform to another have the potential to mitigate the high data variability, as it would produce foot-ground interactions that are more consistent. However, such motor task is not representative of the real motor behavior of infants and children during their every-day activities, which will be explore more in details in the next sections. Therefore, using an unrestricted gait protocol could lead to capture pressure images that are more variable in shape, dimensions as well as spatial orientation. This represent a key point to develop registration approaches that lead to accurate overlap of the pressure images. Accordingly, a rough registration could cause pSPM to find differences between pixels that might not be due to changes in pressure but to the issues with the images overlapping process. Such considerations highlight just some of the challenges present with pSPM and might be one of the reason as to why the literature lacks of studies adopting it to explore plantar pressures of infants and children. Therefore, further work is needed in order to test the implementation of the pSPM data processing framework on infants and children pressure data.

2.3 Synthesis of plantar pressures data from infancy to childhood

This section is a co-authored paper that has been re-formatted for this thesis. The bibliographic details of this co-authored paper including all authors are:

Montagnani E., Price C., Nester C., Morrison SC. (2021). Dynamic Characteristics of Foot Development: A Narrative Synthesis of Plantar Pressure Data during Infancy and Childhood. *Pediatric Physical Therapy*.

DOI:http://doi.org/10.1097/PEP.0000000000000819

I made the principle contribution in the conception and design of the study, analysis and interpretation of the research data and the drafting and critical revising of the final manuscript. Despite the narrative of the paper slightly differs from the present section, tables in the Appendix 2 are reported as in the paper.

Dated: 26.07.2022

Signed:

Eleonora Montagnani

This section aims to offer a summary and critical appraisal of findings from plantar pressure analysis available in the paediatric field, to highlight current knowledge of the typical foot function characteristics and development from infancy to childhood, in addition to strengths, limitations and gaps in the field. Specifically, pressure data will be summarised and described in infancy (section 2.3.1) and early and late childhood (section 2.3.2), and critical appraisal of the literature will be carried out (section 2.3.4).

Age definitions will be aligned to existing plantar pressure studies. Specifically, it has been found that infancy has been defined up to two years of age, as infants learn and master walking abilities (Hennig and Rosenbaum, 1991, Hallemans et al., 2003, Hallemans et al., 2006b, Bosch et al., 2010, Bertsch et al., 2004). Early and late childhood definitions acknowledged the distinction between children being in the pre-school age (3 – 5 years) and school age period (6 – 13 years) respectively (Hennig et al., 1994, Alvarez et al., 2008, Mesquita et al., 2019, Kellis, 2001). A full summary of the articles characteristics will be presented in (Table 11 and 12), and categorised by age of study participants. Pressure variables described within these sections will be expressed and defined in the thesis glossary. It is anticipated that the experimental chapters of the thesis will aim to investigate only plantar pressure data across infancy. However, it is also recognised that gathering information from studies undertaken during childhood has the potential to increase understanding of the limitations present within the available literature, which can improve the development of the thesis.

2.3.1 Plantar pressure characteristics in infancy

Plantar pressure data has been investigated at the earliest from the onset of walking, which defines the period when infants start to take the first independent steps and has been observed taking place between 12 and 15 months (Bertsch et al., 2004, Bosch et al., 2007, Bosch et al., 2010, Hennig and Rosenbaum, 1991). At this point, infants adopted different walking strategies to walk (Bisi and Stagni, 2015), which have been reported in section 2.1.4. With different gait pattern performed by infants at the onset of walking, studies have also explored and analysed centre of pressure (COP) trajectories as indicators of pressure application throughout the plantar surface of the foot, to investigate the typical foot contact patterns performed at this stage (Bertsch et al., 2004; Hallemans et al., 2003; Hallemans et al., 2006b). Specifically, the forefoot was the area of the foot were origin of the COP was visually reported to occur more often (60% of the steps analysed). Visual COP observation also recorded that initial forefoot contact was followed by whole-foot contact (35% of the steps) as the origin of the COP was found to occur across the heel, midfoot and forefoot at the same time. At last, initial contact with the heel was detected less frequently at the onset of walking (5% of the steps) (Bertsch et al., 2004; Hallemans et al., 2003). Accordingly, another study visually analysed foot contact patterns as infants became confident and independent walkers, and found that initial contact with the heel was demonstrated by infants who had more walking experience (+19 months of walking experience compared to infants who just started to walk) (Zeininger et al., 2018). Within few months from the walking onset, the continuous medio-lateral (ML) and anterior-posterior (AP) trajectories of the COP were analysed in the form of averaged values normalised to foot length and width. The available data demonstrated high intra and inter-individual variability of the ML oscillations, which were also large with respect to the foot width, and large AP displacement of the COP at the onset of walking (Hallemans et al., 2003). Reduced ML oscillations and AP displacement of the COP became visible after approximately five months of independent walking experience (Hallemans et al., 2003; Hallemans et al., 2006b), suggesting development of the heel-to-toe pattern of pressure distribution during the first year of independent walking (Bertsch et al., 2004: Hallemans et al., 2006b). Specifically, initial heel contact appeared after eight weeks of walking (Hallemans et al., 2003) and increasingly becomes the typical initial contact pattern after one year of independent walking (Hallemans et al., 2006b), with the COP lying beneath the heel (Zeininger et al., 2018).

It is interesting to notice that in the early 90s a study by Latimer and Lovejoy (1989) found that, in apes, the changes in the calcaneal bone composition (e.g. robustness) and orientation of its articular processes where part of an adaptive loading response to bipedal locomotion that ultimately allowed efficient force dissipation and shock absorption. Zeininger et al. (2018) gave such explanations in relation to the establishment of initial heel contact in early stages of walking development, suggesting that infants started to load the foot with the heel due to the presence of calcaneal bony properties highlighted in Latimer and Lovejoy (1989).

Investigation of plantar pressures showed that the hallux was the most loaded region of the foot during the first eight months of independent walking, with peak pressure values ranging between 120-180 kPa (Bertsch et al., 2004; Bosch et al., 2010; Hallemans et al., 2003; Hennig and Rosenbaum, 1991; Muller et al., 2012). In contrast, peak pressure at the heel ranged between 95.5 kPa and 130 kPa (Bertsch et al., 2004; Bosch et al., 2010; Hennig and

Rosenbaum, 1991), while peak pressure in the forefoot ranged between 78.2 kPa and 110.9 kPa (Bertsch et al., 2004; Bosch et al., 2010). During the first few months of independent walking, pressure values (peak pressures and forces) were higher within the regions of the medial side of the foot (Alvarez et al., 2008; Hennig and Rosenbaum, 1991). After approximately two months of independent walking, absolute contact area and maximum force values increased at heel, forefoot and hallux, and decreases at the midfoot, and these patterns were similar for the normalised values to body weight and expressed as percent of the total value (e.g., contact area) (Bertsch et al., 2004; Bosch et al., 2010). On the contrary, absolute and relative contact time (normalised with respect to the stance phase duration) decreased significantly during the first year of independent walking at the heel, midfoot and forefoot, but increased at the hallux (Bertsch et al., 2004; Bosch et al., 2010), highlighting an overall quicker stance as walking developed. Interestingly, no consistent and evident changes in peak pressure at the midfoot were reported over the periods of observation (Bertsch et al., 2004; Bosch et al., 2010).

2.3.2 Plantar pressure characteristics in early and late childhood

As opposed to infants, greater pressure was applied onto the lateral side of the foot than the medial during walking in early childhood (Bosch et al., 2010; Kellis, 2001) and this still occurred during late childhood (Hennig et al., 1994; Muller et al., 2012). For example, an early observation has found that the difference in medio-lateral load increased by 3.1% in six years old children compared to 1.9% in 10-years old, indicating that six years-old children still experienced a higher relative medial pressure distribution compared to the older group (Hennig et al., 1994). By the age of two years, children demonstrated a constant initial contact with the heel during walking, and the heel became the most loaded region in both early and late childhood (Bosch et al., 2010; Phethean and Nester, 2012). As an example, in early childhood, peak pressure at the heel ranged between 169 kPa and 212.5 kPa (Bosch et al., 2010; Kellis, 2001), with the lateral heel being subject to higher peak pressure (119 kPa) than the medial (99 kPa) (Hennig et al., 1994; Kellis, 2001). In late childhood, pressure at the heel continued to increase, remaining the most loaded region of the foot (280 kPa) (Phethean and Nester, 2012). A decrease in normalised contact time occurred between early and late childhood in heel, medial and lateral midfoot, medial and lateral forefoot (Alvarez et al., 2008; Bosch et al., 2010) but significant changes occurred mainly at the medial and lateral midfoot and at the lateral forefoot, as demonstrated by Alvarez et al. (2008). In early and late childhood, there was still a trend of increasing contact area and maximum force at the heel, forefoot and hallux and decreasing values at the midfoot. Specifically, forces decreased in the medial midfoot and increased in the lateral forefoot in early childhood (Alvarez et al., 2008), which is in accordance with other studies (Phethean et al., 2014). Comparison of different types of analysis (regional analysis and pSPM) demonstrated that pressure also increases in the central metatarsals during late childhood. Yet, studies did not report changes in peak pressure within the midfoot (Bosch et al., 2010; Muller et al., 2012). Furthermore, a study analysing force-time integral values in a population of children aged between seven and 14 years found that impulses in the midfoot decreased with age, and the curve of medio-lateral forefoot balance was increasingly shifted medially compared to infants aged between two and six years (Dulai et al., 2021). The authors also reported that by late adolescence, values of 15-17 years olds were comparable to those in adults.

2.3.3 From plantar pressures to foot function development: up-to-date knowledge and considerations

2.3.3.1 Infancy

One of the most important aspect to consider in the plantar pressure research field is that the above section reporting infants data demonstrated lack of investigations prior to the establishment of walking, ignoring the presence of typical plantar pressure patterns as infants develop different forms of bipedal locomotion, such as during pull-to-stand and cruising. Nevertheless, the review of the literature highlighted that, in infancy, there were evident differences in plantar pressures with increasing walking experience, with continuous changes taking place during the first year of independent walking. Accordingly, infants at the onset of walking showed typically immature foot-ground interactions, which developed quickly as ML oscillations of the COP reduces and pressure application from heel to toe became evident after five months of independent walking experience (Bertsch et al., 2004; Hallemans et al., 2003; Hallemans et al., 2006b). This was supported also by a more recent work, whereby COP trajectories where described with respect to the initial contact patterns made by infants (Zeininger et al., 2018). As a result, these works enabled speculation about the development of foot-ground interactions that changed towards a heel-to-toe pattern of pressure application.

These studies, however, presented substantial limitations. For example, Zeininger et al. (2018) identified contact pattern changes by visually reporting the types of contact made during walking, also analysing a small number of steps overall (N=63) and for each infant (N_{min}=2; N_{max}=5), which cannot account for wider intra- and inter-individual characteristics of foot loading patterns and their changes in infancy. Similarly, Bertsch et al. (2004) and Hallemans et al. (2003) performed visual observation of the COP by describing its progression throughout the plantar surface of the foot. Such observation was limited not only because it lacks of quantifiable changes, but also because the authors did not consider COP trajectories in its ML and AP component. According to Winter (1993), AP and ML component of the COP express information related to dorsiflexion and inversion-eversion motor responses, respectively, thereby highlighting different information associated with COP changes.

As a result, distinguishing the COP data interpretation in its ML and AP component is essential to capture in-depth of information associated with foot-ground interactions changes in infancy, supporting the premises of their independent analysis with respect to each other. Hallemans et al. (2006b) reported COP analyses in its ML and AP dimensions. However, their work was characterised by analysis of 10 infants, using low-resolution statistical approaches and extracting average values representing temporally meaningful vectors, and were normalised to foot length and width. Therefore, there were not considerations related to changes occurring across the entire stance. In addition, the works from Hallemans and colleagues (2003; 2006b) extracted scalars from the whole ML and AP components of the COP. a comparison between vector field and scalar analyses highlighted that scalars from the ML component of the COP are sensitive to the COP coordinates system (Pataky et al., 2014). Although this analysis was performed considering an adult population, this is an important factor to consider also in the analysis of infants' pressure data, especially if it originates from free and unrestricted gait protocols, where contact patterns and feet placement onto the pressure platform is highly variable (Price et al., 2017) and might affect scalar extraction.

With these limitations, it is difficult to say whether the establishment of the typical heel-to-toe pattern of pressure application can be reported with certainty according to the available data, and this field of pressure analysis should be revised in future works. Nevertheless, the above findings make reasonable to assume the presence of improved foot-ground interactions in the transition to confident walking. Such considerations however have to be made also in relation to plantar pressures and their modifications with more walking experience. Accordingly, studies demonstrated that the amount of pressure applied onto the plantar foot surface was also subject to rapid changes from the onset of walking. Specifically, the increasing pressure in the heel and forefoot occurring alongside decreasing pressure in the hallux might be caused to the changes in pressure application occurring in the transition to confident walking (Bertsch et al., 2004; Bosch et al., 2010; Hallemans et al., 2003; Muller et al., 2012). In other words, changing the way pressure is applied throughout the plantar surface of the foot has the potential to cause modification in the quantity of pressure applied in certain areas of the foot. Nevertheless, linking the findings of these studies would not be a trivial task, especially considering that pressure data was not collected and analysed with respect to a common sample, and studies presented also differences in the testing protocol adopted and the data collection equipment used. Therefore, discrepancies among the available studies does not allow to converge plantar pressure results towards a common data interpretation, which would provide an in-depth understanding of foot function development, underpinning research and clinical practices.

Furthermore, plantar pressure patterns and changes in infancy can be predicted also by a variety of factors associated with maturation and development such as variations in body weight, height, walking experience and speed. These are important factors to consider in the plantar pressure field, as they would enable to increase understanding of the changes in pressure occurring during walking development. However, the type and strength of the relationship between body weight and height and plantar pressures in infancy has been reported only once (Bosch et al., 2010). Accordingly, studies have focussed on changes related to foot morphology and pressures occurring in children who are obese, overweight and typical-weight (Cousins et al., 2013, Dowling et al., 2004, Mauch et al., 2008, Riddiford-Harland et al., 2000). In addition, only one study used the increasing walking experience as a predictor to explain changes in plantar pressure using COP data analysis (Hallemans et al., 2006b). Finally, Hennig and Rosenbaum (1991), analysed infants aged 23.5 months, identifying statistically increasing pressure in the central forefoot between trials of walking and running, showing that differences in walking speed influence the amount of pressure applied on the foot.

It is also important to highlight that plantar pressures were also reported to be different between boys and girls in infancy. Accordingly, Unger and Rosenbaum (2004) analysed a group of 20 boys and 22 girls for one year after they started to walk independently (mean baseline age 16.1 months). The authors found that girls showed higher peak pressure in the forefoot and heel, while boys demonstrated higher peak pressure, force and contact area in the midfoot. Moreover, differences in pressure patterns highlighted that boys demonstrated a slower roll over pattern in comparison with girls, who showed higher and faster pressure applied in the heel and forefoot during walking. It is difficult to say whether these alterations were due to actual differences between boys and girls, or if other factors need to be accounted for, such as high intra and inter-individual variability in plantar pressures and the differences of body weight within each group, for example. Unger and Rosenbaum (2004) isolated and compared a small subsample of boys (n=7) and girls (n=7), to exclude that difference were due to potential variances in body weight. Because of this analysis, the authors reported that the differences were moderated by gender, instead of variations in body weight between males and females (Unger and Rosenbaum, 2004). Nevertheless, comparing body weight of such a small sample might be not indicative of absence of differences in body weight as inter-individual variation in mass might be high. Therefore, future considerations should be made in this context to ensure whether conducting further studies to detect changes in pressures between males and females could provide insight related to modulation of foot function development by sex differences in infancy.

2.3.3.2 Early and late childhood

As opposed to research conducted in infancy, pressure studies in early and late childhood have separated plantar pressure analysis between boys and girls age from four to 10 years, and they did not find any difference in plantar pressure patterns (Phethean and Nester, 2012, Hennig et al., 1994). This might support the premises that the differences between plantar pressure of males and females infants highlighted in Unger and Rosenbaum (2004) were possibly unrelated to sex-specific differences in foot function and might be a consequence of the high intra and inter-individual variability of pressures and foot contact patterns.

Despite these initial considerations, it has been reported that peak pressures were increasingly applied onto the lateral surface of the foot during walking in early childhood (Kellis, 2001). Findings from the literature confirmed that such pattern was also present during late childhood (Alvarez et al., 2008; Muller et al., 2012). However, the medial side of the foot still experienced higher peak pressure and forces in comparison with the lateral in early childhood (Hennig et al., 1994). Several factors could influence typical plantar pressures during walking at this stage, and they could be mainly related to lower limb and foot posture coupled with the developing foot structures. Accordingly, children’s feet are characterised by high flexibility and laxity (Malina, 2004), which could inhibit the foot to act as a full rigid lever. The effects of the developing foot structures to plantar pressures were also supported by Phethean et al. (2014), who analysed the influence of increasing age to plantar pressure in sample of children aged between four and seven years. Specifically, the authors argued that the pattern of increasing central forefoot loading highlighted from the analysis was the consequence of high joint laxity that prevented pressure being efficiently distributed from the 5th to 1st metatarsal heads as it occur with adults (Rai and Aggarwal, 2006).

In addition, the ankle was in an everted position during walking up to 5 years of age (Samson et al., 2011). All these factors considered suggest that a persistent medial foot loading might be due to a combination between the developing foot structure and ankle posture, preventing to capture increasing lateral foot pressure in early childhood. The present findings therefore emphasised that plantar pressures continue to change, highlighting the ongoing foot function development in the transition from early to late childhood. This is supported also by the medial shift of the medio-lateral forefoot balance reported by Dulai et al. (2021), associated with higher impulse values in the medial forefoot compared to the lateral, suggesting the presence, in the terminal phase of stance, of a more powerful push-off than in earlier stages of development. In general, studies also reported that in late childhood, changes in foot function were characterised by overall increasing pressure and force values across the foot regions as well as decreasing contact times (Bosch and Rosenbaum, 2010, Dulai et al., 2021, Mesquita et al., 2019, Muller et al., 2012a). A recent work examined a population of children aged between 11 and 14 years (Demirbüken et al., 2019) and found that with increasing age, values of peak pressure and force were the highest at 14 years of age respect to the younger age group, along with an increased area of contact. The increasing age is, however, an indicator of the overall growth and development, which therefore accounts for changes of processes related to both maturation and development that should be analysed separately.

Studies in childhood used typical body weight variations to predict foot function changes, although such studies were undertaken with respect also to children who were obese and overweight. Using body weight as main predictor to foot function changes in late childhood can be justified as this is a key period when obesity start being increasingly present, according to the World Health Organisation (WHO). In fact, the WHO stated that in 2016, 124 million children and adolescents aged between five and 19 were obese. Consequently, variations in body weight should be monitored closely during late childhood, to avoid establishment of atypical function of the foot that could lead to musculoskeletal pain and discomfort during growth. For example, it has been found that between seven and 11 years of age, children who were overweight and obese displayed higher peak pressures at the midfoot, second and fifth metatarsal heads in comparison with typical weight children (Cousins et al., 2013). Changes in typical pressure patterns might not be an issue per se, but it is important to highlight that the continuous overload might cause stress of the delicate foot structures in childhood (Mickle et al., 2006), which could consequently lead to pain, discomfort and functional impairment that would require intervention.

With body weight, variations in other systems should also be considered in relation to foot function changes. Accordingly, Rosenbaum et al. (2013) demonstrated that increasing walking speed caused changes of plantar pressures in eight years-old children, with peak pressure being significantly higher in the heel at fast speed compared to slow speed. With these considerations, it is therefore possible to say that during late childhood, the acceleration forces gathered during swing are released within the heel at initial contact and become partially absorbed by its anatomical structure. Once the heel makes initial contact, the ground reaction forces generated by foot-ground interactions are transferred throughout the midfoot and forefoot and finally reach the hallux, which also experience higher and quicker transfer of pressure and forces as body weight is propelled forward. Changes in foot function however do not stop with late childhood but have been also reported that in the transition to late childhood to adolescence. However, when a group of 15-17 years old (n=21) was compared to a group of adults (n=60), no differences were detected in plantar pressure values, suggesting that by the adolescent period, foot function changes arrest (Dulai et al., 2021). Nevertheless, there were differences for the sample size analysed in the two groups (21 vs 60), and therefore, future studies should confirm the present findings by relying on data sets generated from equal sample sizes.

2.3.4 Characteristics of the existing literature

In the previous sections, foot function characteristics and development have been described through plantar pressure analysis from the onset of walking. Although the onset of walking represents one of the major motor achievement in infancy, there are currently no studies looking at plantar pressures in infancy prior to the onset of walking. Investigating plantar pressure patterns only during stages of walking would inevitably lead to ignore important information about the typical foot function characteristics in early motor development, which has yet to be explored.

Heterogeneous choice of study designs, sample definitions, testing protocol and data analysis approaches have been identified within the existing literature. For example, testing protocols did not always isolate supported and independent steps detected by the pressure platform. In fact, steps where infants were walking supported, for example by parents, were combined in some instances to independent walking trials (Bosch et al., 2010). As parents partially supported infants' body weight, it has been anticipated the presence of different plantar pressure patterns in supported walking compared to the independent steps, and averaging this data could be misleading. For example, Ivanenko et al. (2005) demonstrated that supporting infants during walking by holding their hands lead to statistical differences in some spatial-temporal parameters of gait, making it reasonable to assume that it could affect also plantar pressure data.

Therefore, whilst all weight bearing conditions or tasks of the foot are useful to understand as they may affect foot development, different functional tasks should be investigated independently of each other. Specifically, since walking supported and unsupported walking are recognised motor milestones, it follows that the contribution of the foot should be considered under these separate circumstances. Moreover, it has been observed that testing protocols consisted of either free walking trials (the child walks freely in any direction over the pressure platform), directed walking trials (the child is asked to walk repeatedly on the pressure platform in straight lines) or both combined. Allowing children to walk freely during the testing would resemble the activity performed in their habitual setting (Adolph et al., 2018). In other words, instructing infants and children to walk just across the pressure platform is not representative of the real-world walking patterns adopted during their every-day activities. For example, Adolph et al. (2018) reported that start and end point during walking are chosen arbitrary by infants and children, suggesting that the typical walking patterns in infancy and childhood is far from straight lines, which have been however largely adopted by previous works. As such, capturing pressure data of infants walking in self-selected directions would enable researcher to detect the real-world walking patterns and foot function characteristics of the paediatric sample.

Finally, studies selected their sample based on either developmental milestone or age groups with also a preference for cross-sectional rather than longitudinal studies. Development is a cardinal point to consider within the paediatric populations as inter-individual changes occurs at different time. As an example, infants are likely to reach specific ambulatory stages at different ages, likewise children, who may be able to perform different motor tasks at different ages. Then, the choice of categorise samples based on their age instead of their motor development may be consider inappropriate within developmental contexts. Furthermore, cross-sectional evaluations tends to average potential changes (Alvarez et al., 2008; Hennig and Rosenbaum, 1991; Muller et al., 2012) whereas longitudinal studies could be able to extrapolate also intra-individual motor developments and thus could be better used to monitor and describe changes growth-related during different motor task. Thus, identifying the cohort of plantar pressure studies based on motor stages would be more appropriate than age, avoiding generation of erroneously averaged pressure patterns of population at different motor stages.

When looking at data analysis approaches, similar plantar pressure studies have produced a large variety of data processing protocols, thus outcomes are difficult to compare between studies. An interesting finding to report is the trend of changes at the midfoot from infancy to childhood have been reported following a path of increasing and decreasing values in infancy (Bertsch et al., 2004; Bosch et al, 2010) and childhood (Bosch et al., 2010), which may be due to different reasons.

As discussed in previously (section 2.2.3.2), analysis of plantar pressure patterns has focussed exclusively on anatomical regions of interest, mainly the heel, midfoot, forefoot, hallux (Alvarez et al., 2008; Bertsch et al., 2004; Bosch et al., 2010; Mesquita et al., 2018; Muller et al., 2012). Concerning the midfoot, most of the studies reported data for the entire region as opposed to medial and lateral midfoot (Alvarez et al., 2008; Bertsch et al., 2004;; Bosch et al., 2010; Hennig and Rosenbaum, 1991; Mesquita et al., 2018; Muller et al., 2012). Thus, any changes of both medial and lateral sides have been generalised. This could therefore means that the peak pressure value is detected in the medial and the lateral regions without discerning where it is precisely. Nevertheless, by selecting a methodology which divides the midfoot in its medial and lateral components, researchers could imply that the midfoot is already a functional unit in infants. This assumption is highly controversial due to the overall developing walking abilities, immature midfoot structure (development of MLA, slow ossification process of the tarsal bones, high proportion of plantar adipose tissue) and function that could prevent the midfoot to be considered as a typical functional unit. This can be assumed as the reason this analysis has not been undertaken in infancy yet.

In early and late childhood, division in medial and lateral midfoot has been adopted. Specifically, Phethean et al. (2014) found that peak pressure increases with age in most of the foot regions but when the forefoot and midfoot were divided in the lateral and medial components, the third metatarsal head and the lateral midfoot were subject to the highest peak pressure. This indicates that if regional analysis was adopted, a further division of the foot regions in their medial and lateral components would be needed, to avoid detecting higher homogeneity in pressure patterns and thus less changes. This further division could allow researchers and clinicians to draw clearer consideration regarding infants and children foot function changes. Nevertheless, it is still not clear whether increasing the amount of regions to analyse in infants pressure studies would align with the developing foot structure characteristics at this stage. As proposed by Phethean et al. (2014), a more novel approach to pressure data (pSPM) in paediatrics could be adopted to solve the limitations related to masking analysis approaches. However, works are warranted to illuminate about the application of the different approaches to pressure data as well as their findings in relation to foot function development.

As general conclusion of these section, it is possible to state that two key points have to be highlighted: first, reliable and more objective information related to foot function development in infancy and childhood might be obtained using a data collection and testing protocol that consider pressure data captured in real-world environments. Second, adopting a continuous analytical approach, such as pSPM, might provide more detailed and meaningful insights about the plantar pressure patterns and their changes from within infancy, early and late childhood.

2.3.5 Foot conditions in infants' clinical practice

Despite the gaps and limitations of the wider literature have been presented in the above section, it is clear that previous works in the field of developmental biomechanics have captured and analysed plantar pressure data to try and map the typical trajectory of foot function development occurring in infancy and childhood. This is clinically relevant when clinicians observe populations that are not following a typical development in their every-day practice, as it can help establish the presence of atypical foot function development, as well as target and monitor intervention efficacy.

In infancy, several conditions can affect the typical foot function characteristics and development. For example, it has been reported that, at birth, infants can be affected by musculoskeletal and neurological disorders impacting the typical development of their feet (Hart et al., 2005). Musculoskeletal foot conditions include, for example, metatarsus adductus, positional clubfoot, and calcaneus valgus, whilst neurological syndromes affecting the foot are congenital equinus-varus foot, congenital vertical talus and toe deformities (syndactyly, polydactyly) (Hart et al., 2005).

It is not fully reported how plantar pressures are affected by such conditions when the foot starts being a weight bearing structure in infancy, as there is scarcity of studies using plantar pressure technologies to investigate foot function in infants at early stages of motor development. Accordingly, studies adopting plantar pressure platforms in infancy have mainly focussed on typically developing cohorts, and findings have been extensively reported in section 2.3.1 and 2.3.2. This gap in the knowledge related to plantar pressure profile of atypically developing infants populations can be caused by several factors. First, musculoskeletal and neurological conditions affecting foot development in infants are generally treated before the infants' feet start bearing weight (Widhe, 1997). There are also cases where foot pathological conditions also do not need treatment. For example, it has been found that 95% of feet presenting metatarsus adductus resolve spontaneously as infants grow (Weinstein, 2000). Second, it has been demonstrated that parent lack of awareness related to the importance of the infants' foot health (Hodgson et al., 2021), which can lead them to ignore consultations with foot health practitioners as part of routine health visits for their infants. This was discussed also to be caused by the lack of understanding that referrers (e.g., general practitioners) have about foot health disciplines (Hodgson et al., 2020), highlighting the importance to improve referral pathways through raising training and awareness about paediatric foot health.

As a result, it is not surprising that there is currently scarcity of studies adopting plantar pressure analyses to map foot function characteristics and development in infants presenting foot conditions. Specifically, the literature reports only two studies assessing plantar pressures in infants who were affected by idiopathic clubfeet (Jeans and Karol, 2010, Jeans et al., 2014). Accordingly, it has been showed that infants with clubfeet demonstrated higher-pressure values in the lateral midfoot and a less medial displacement of the centre of pressure compared to typically developing infants, due to the adductus position of the foot that prevent medial pressure distribution (Jeans and Karol, 2010, Jeans et al., 2014).

Despite this lack of knowledge about plantar pressure characteristics of infants with different foot conditions, it is reasonable to state that some of the pathological situations mentioned above could lead to experience atypical foot function characteristics and development across childhood, which can be captured with plantar pressure assessment. For example, it has been demonstrated that children at the age of six who undertook surgical intervention to correct clubfeet deformities experienced different pressure distribution values compared to the typically-developing control group (Salazar-Torres et al., 2014). Such differences included lower peak pressure in the heel and forefoot and higher loading in the lateral midfoot compared to the control group (Salazar-Torres et al., 2014). Similarly, plantar pressures of a group of eight-year old children affected by valgus calcaneal deformity associated with cerebral palsy were observed before and after two corrective surgeries (Park et al., 2008). As a result, the authors were able to demonstrate that after surgery, children experienced plantar pressure distributions and center of pressure progression that were close to the typically developing control group, although not the same (Park et al., 2008).

With this information, it is therefore likely that foot conditions that are not recognised in infancy, or that are not treated promptly, would cause atypical foot function development across both infancy and childhood. As a result, mapping the typical development of foot function can help clinicians recognise when atypical foot function patterns are present, which can aid early intervention and assess treatment efficacy.

2.4 Summary and gaps in the knowledge

This chapter highlighted the unique complexity of neuromuscular-skeletal maturation, which have an impact on postural control and motor changes occurring throughout the paediatric age. With concurrent changes taking place in the different body systems, infants and children attain several milestones when the function of the foot continuously develops. Among the approaches to explore foot biomechanics, plantar pressure analysis will be used in this thesis, and its methodological applications to analyse paediatric plantar pressure data have been reported alongside its strengths and limitation. Specifically, two main approaches to plantar pressure data analysis exist, namely masking analysis and pSPM.

Advantages of masking analysis were represented by its user-friendly interface, the possibility to process a high number of data and without the need for specific statistical packages as well as its high flexibility in relation to the research questions and hypotheses to be tested. Such advantages caused masking to be widely used in the paediatric plantar pressure field. However, regions of interest were detected on the plantar surface of the foot based on hardware designs scaled for typically developed feet and contact patterns practiced by adults, which are not representative of the real anatomical and functional characteristics of infants and children's feet. This causes a further reduction within the spatial resolution of pressure data, as there are also no boundaries on the plantar surface of the foot, increasing potential loss of information. Alternatively, pSPM is a novel, exploratory approach to pressure data analysis that aims to handle pressure information entirely, and without discrediting or reducing data resolution. However, application of pSPM have been reported mainly in relation with adults' pressure data, with scarce application being reported in paediatrics.

Given these considerations, it is possible to state that there is a lack of exploration of methodological approaches to paediatric pressure data. Thus, there is need to establish the optimal methodological approaches in this field, to increase resolution of data analysis, improving data interpretation hence knowledge of foot function development in paediatrics. Accordingly, the existing literature exclusively adopted masking analysis to study the typical plantar pressure patterns and their changes in infancy, with only one study reporting its use to study plantar pressures of children. Characteristics of pressure application through COP analysis have also been reported in infancy, even though scarcely and separately from regional pressure data, which limits considerations related to the overall functional characteristics and changes of the paediatric foot. Accordingly, regional pressure data can provide limited information related to the overall changes in plantar pressures, as representative only of the amount of pressure applied onto the specific areas of the foot. Combining information from analysis of different plantar pressure data (such as the COP) has the potential to increase knowledge of the foot function changes, which has to be considered for development of future works. In addition, it would also be important to consider, for example, the relationship between body maturation (e.g. body weight, height, foot dimensions) as well as the walking experience with plantar pressures, which could predict plantar pressures changes. These analyses come with some limitations in the literature, as studies were inconsistent in reporting their relationship with plantar pressure data with respect to both infants and children. For example, the use of body weight as predictors of plantar pressure changes have been reported comparing pressure data of children who were obese, overweight, and typical weight, with scarce considerations made relating to typically developing infant cohorts.

By scoping the existing plantar pressure literature, some limitations have also been recognised in terms of study design, testing protocols, data collection and sample definition among the studies, alongside the data analysis approaches aforementioned. To summarise briefly, studies have explored foot function development from the onset of walking, without considering functional characteristics of the foot prior to walking establishment. In addition, previous works adopted combination of both longitudinal and cross-sectional designs, defined sample both based on age or motor milestone attainment, and mixed the analysis of pressure data generated from either supported, independent walking or both. In the context of analysing developing infants, the presence of systematic gait protocols do not consider their unique motor development, which could impacting on pressure data interpretation, affecting knowledge of the real-world foot function patterns and changes across infancy.

Therefore, findings from this review highlighted the lack of works combining different plantar pressure data as well as predicting plantar pressure changes using variables related to body maturation (e.g. increasing body weight, height, and foot dimensions) and walking experience, especially in infancy. As a result, there is need to develop a specific research protocol and methodological approaches to plantar pressure analysis, designed to overcome the challenges previously highlighted when foot biomechanics of infants is investigated. This would have the potential to provide a better understanding of foot function characteristics and development in paediatrics.

Thus, the main gaps and limitations identified by this review in the field of infants' plantar pressure analysis can be summarised as follow:

- The lack of methodological investigation of the available approaches to analysis of pressure data;
- The absence of a research protocol that enable capturing real-world plantar pressure data as walking experience increases;
- The absence of plantar pressure information prior to the establishment of independent, confident walking (e.g. pull to stand);
- The lack of in-depth considerations related to plantar pressure application and changes occurring over stance with increasing walking experience through high-resolution analysis of centre of pressure data;
- The absence of high-resolution statistical comparison of plantar pressure data between infants at the onset of walking and confidently walking;
- The lack of analysis to predict changes in plantar pressures across stages of walking development;

Therefore, the following experimental chapters aim to fill the aforementioned gaps, overcome limitations and to provide the wider scientific community with an improved knowledge of foot function characteristics and development as infants passing from pull to stand to confident walking.

Chapter 3. Materials and methods

The materials and methods reported hereafter were used for the each of the following experimental chapters (chapter 4, 5, 6 and 7), and thus, these will not be fully reported within the individual chapters.

3.2.1 Ethical approval

The experimental chapters within this thesis were regulated by Ethical approval granted from the ethics panel within the School of Health Sciences University of Brighton (LHPSCREC 17–11) and the University of Salford (HSCR161779).

3.2.2 Recruitment

Recruitment took place in the South East and North West of England, around the areas in proximity of the University of Brighton (Eastbourne) and University of Salford (Salford), respectively. Strategies related to the recruitment process included engagement with parents through distribution of flyers and posters to community groups and facilities, such as church groups, yoga, and baby massage groups as well as participation of researchers at baby shows (Appendix 1). Infants were also recruited via social platforms (Facebook, Twitter) through creation of posts advertising the project and data collection requirements at the respective University campuses. In some instances, coffee morning sessions with parents were held, so that parents with their babies could come to the area dedicated to data collection within the Universities.

3.2.3 Participants

Infants were eligible to take part into data collection if they were born within 37-42 weeks of pregnancy, had no signs or history of musculoskeletal and/or neurological disorders, audio, visual or sensory impairment, and were born above the 4^{th} percentile for weight. Parents reported such information at the moment of the first communication with the primary researcher. They were excluded if they had been referred for consultation for suspected musculoskeletal or neurological condition, had a family history of neurological and musculoskeletal conditions (e.g., juvenile idiopathic arthritis, Charcot Marie Tooth) and they were taking medicines (indicator of health issues). Infants were also excluded if they attended the data collection sessions later than six months after the expected attainment date.

3.2.4 Data collection

The data collection protocol adopted in this thesis aimed to capture habitual, real-world motor behaviour in infancy. Data collection sessions were conducted at the Human Movement Laboratory at the University of Brighton and within a bespoke laboratory at the University of Salford, which were also referred to as baby spaces or baby labs. The area of data collection was decorated with toys and stickers to be similar to a nursery-style, friendly environment, resembling the typical space infants are used to during their daily activities. As part of the Great Foundations program, plantar pressure data was collected at four different stages of development, specifically when infants started to grab their feet, when they started to pull up to stand, to walk independently and to walk independently and confidently (Figure 6). For this thesis however, only infants from the stage of pull to stand were considered in the observational analysis.

If interested, and the infants were eligible to participate, parents were asked to contact the researchers as soon as the infants were able to pull up to stand against furniture (sofa, chairs, and coffee tables) or against the parents. Participants performed the intended motor task over an EMED xl pressure platform (Novel, Munich, Germany), a system comprised for 25,344 capacitive sensors, collecting at 100 Hz and with a sensor resolution of 4 sensor per cm^2. The platform was of dimensions 1.53m × 0.5m × 18mm for width, length and thickness and embedded in a laboratory space of 2.10m x 1.80m for width and length, respectively (Figure 7). The area around the platform was covered with a soft mat (Figure 7, green background), to ensure test safety and to ensure the platform was flush within the surrounding floor and to avoid the presence of uneven surfaces. At each visit, videos were also recorded simultaneously with initiation of plantar pressure data collection (University of Brighton: Vicon Bonita 720c; Oxford, U.K/ University of Salford: Logitech HD Pro Webcam).

Figure 6. Example of infants pulling up to stand (left), at the onset of walking (central) and confidently walking (right), defining the stages used in this thesis to define motor development.

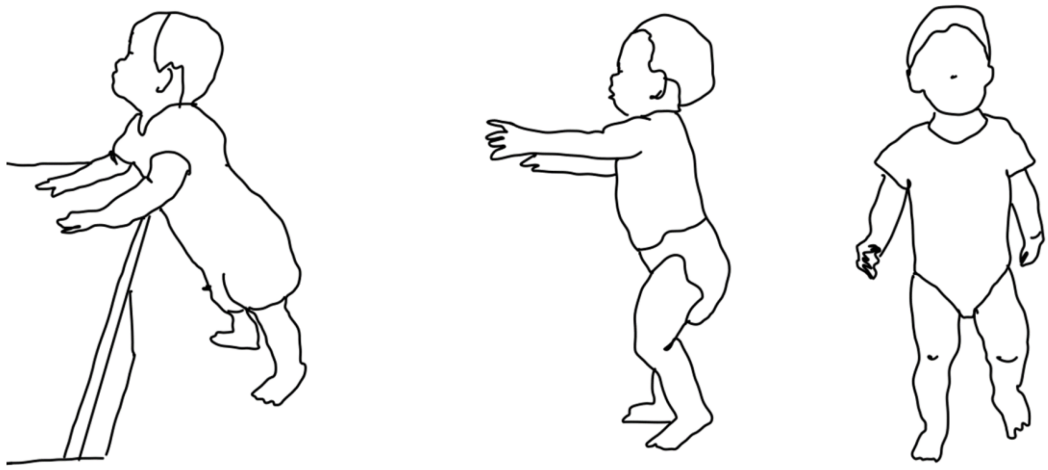
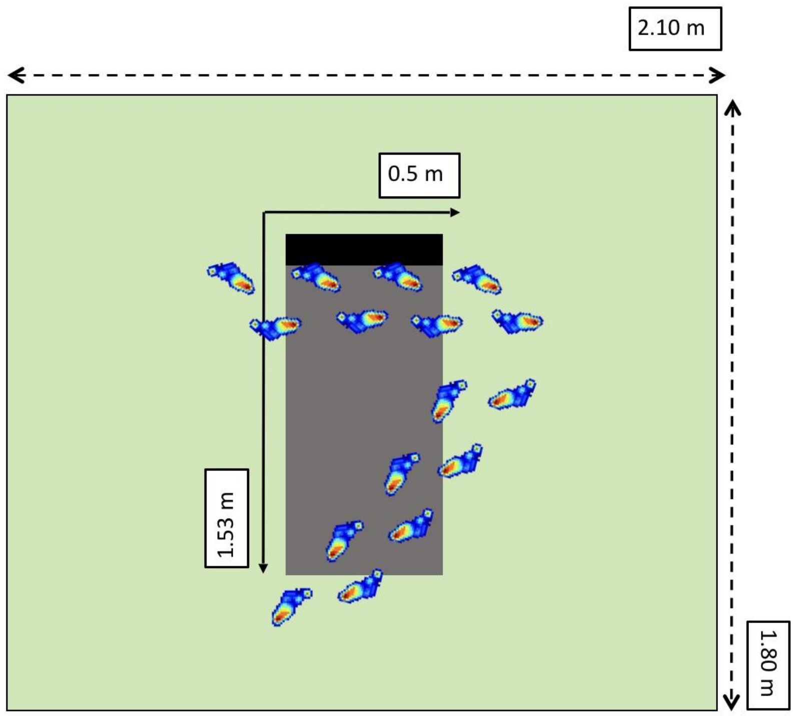


Figure 7. Example illustration of the data collection space, with the EMED xl platform at the centre of the playground, surrounded by soft mat (in green).

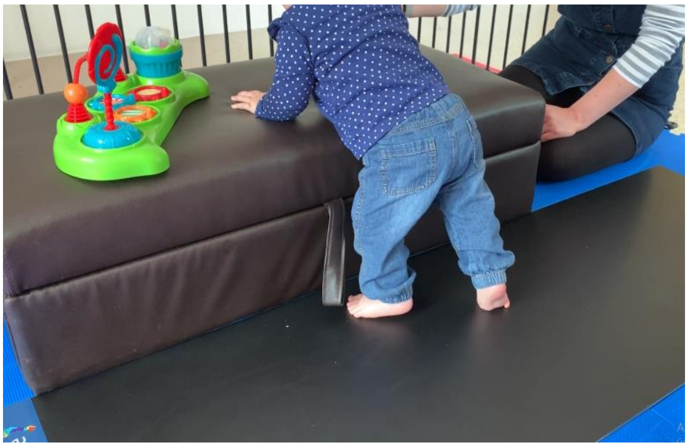


The three milestones will be referred to as first (V1), second (V2) and third visit (V3) respectively. Parents had to identify the milestone attainment of their babies. To help them in the milestone recognition, parents were provided with the necessary informative material (Appendix 1). Once infants reached the milestones, parents that agreed to participate were invited to the University for testing, and they had to attend each visit within 21 days since the attainment of the milestone. If more than 21 days passed, parents were not asked to come for that visit, but were able to attend the following visits, for which data was considered cross-sectional. This cut-off was arbitrarily chosen to capture data of infants that was not too advanced within the milestone of interest. Definition and procedure undertaken for each of the visits were defined as follow:

i. **Pull to stand (V1) -** The first visit consisted of capturing pressure data of infants pulling up to stand onto a low household furniture (foam box) (30cm × 30cm × 100cm) and maintaining the static position. During the first visit, infants were free to cruise along the foam box, if able to do so, which was placed at the edge of the long side of the pressure platform (Figure 8). During this visit, parents or researchers tried to encourage infants to pull to stand by positioning on the other side of the foam block. Infants were free to pull to stand using any strategy or method they liked if they did it independently. Pressure was triggered when infants were either sitting or crawling towards pull to stand position, to capture data once they pulled to stand.
ii. **Onset of walking (V2)** – The second visit consisted of capturing pressure data of infants taking three to five steps independently and on more than one occasion, defining the infants at the onset of walking skills acquisition, who will also be referred to as new walkers. During the visit, infants were free to walk in any direction and they were not instructed to walk over the platform, to capture the most natural establishment of the preferred motor task (for example walking, turning, and squatting). Parents were asked to encourage the infants to walk if they were not willing to do so by grabbing toys and playing with them. Pressure was triggered when infants started walking and left on for 60 seconds. A minimum of three trials of 60 seconds each were requested.
iii. **Confident walking (V3)** - The third visit consisted of capturing pressure data of infants taking 10-15 steps independently, grabbing toys from the ground and carrying them around, interacting with parents while walking, navigating around objects and walking on different surfaces. The third visit aimed to define infants that regularly

walked independently and confidently, which is why infants at this stage will also be referred to as confident walkers. Again, infants were free to walk in any direction and they were not instructed to walk over the platform. Parents were asked to encourage the infants to walk if they were not willing to do so by grabbing toys and playing with them. Pressure was triggered when infants started walking and left on for a one minute. A minimum of three trials were requested.

Figure 8. Example of infants performing pull to stand.



At each visit, parents were asked to fill in an informed consent, and demographics data of the infants were collected using a flexible tape as:

i. Foot length – from the posterior border of the heel up to the big toe;
ii. Foot width – from the medial border of first metatarsal head to the lateral border of the fifth metatarsal head;
iii. Leg length – from the femoral head to the lateral malleolus;
iv. Tibia length – from the tibial head to the lateral malleolus;
v. Height – from the apex of the head to the heel;
vi. Weight – baby positioned onto an analogic scale;

This procedure gave 10 minutes to the participants to familiarise with the new space and the researchers.

3.2.5 Data treatment

Pressure data for both left and right feet were extracted as single files from the main pressure trials using the 'define period tool' in the standard EMED software (Novel, Munich, Germany). This software enabled the segregation of the pressure trial by time such that the feet placed in the same spatial domain of the pressure platform could be separated from each other. To do this, frames of the trial for phases of pull to stand and walking were saved as separate sections including pressure data from each foot, which were spatially independent. Subsequently, pressure data within the selected frames was extracted singularly using the manual 'select free line tool' from the standard EMED software and saved in the form of maximum pressure pictures (MPPs). In each visit, MPPs were coded based on the motor tasks performed by infants within each visit. This was a straightforward process in trials of pull to stand, as infants only:

- Pulled to stand: infants accomplished bipedal upright posture by pulling up to stand against a support;
- Stood supported: infants stood supported;

On the contrary, allowing infants to walk freely across the baby space enabled them to accomplish a series of motor patterns, namely:

- Walking in straight lines: steps originated by infants walking from start to end points following an imaginary straight line without changing direction; it has to be recognised that these steps might not be necessarily straight, as the infants' way of walking in straight lines might also include steps with toes pointing outward or inward.
- Walking in curved paths: steps originated by infants walking while changing direction towards left or right;
- Squatting: steps originated by infants stopping while walking and squatting by flexing the knees;
- Standing: steps originated by infants standing for at least five seconds;
- Non progressing: steps originated by infants stepping in place;

As a result, the researcher coded the nature of pressure data using video trials. To ensure that identification of the pressure tasks of walking trials was consistent across Brighton and Salford, two researchers coded pressure data of 10 infants to determine inter-rater reliability of the data treatment process. Values of interclass correlation coefficient (ICC – model 3, 1) were high between the two researchers, with values ranging between 0.77-0.99, median 0.98. Pressure data were labelled and individually saved for each participant. For the purposes of the following chapters, only data of pull to stand and walking in straight lines were used, with the only exception of chapter 4, section 4.2, where both data of pull to stand and supported standing have been used to increase the data set.

Chapter 4. Establishing the optimal approach(es) to analysis and interpretation of plantar pressure data in infancy

4.1. General background

In the field of paediatric plantar pressure analysis, two main methodological approaches have been proposed and adopted over the years, such as regional analyses and pedobarographic Statistical Parametric Mapping (pSPM). This chapter of the thesis intended to adopt different methodological approaches to plantar pressure data, to establish the optimal approach(es) to analyse, report and interpret plantar pressure data in infancy. To do so, the following studies will be undertaken, and presented as two separate papers:

i. Comparison of two automatic masking approaches to analyse plantar pressure data in infancy.
ii. Pedobarographic statistical parametric mapping of plantar pressure data in new and confident walking infants: a preliminary analysis

This chapter will constitute an important methodological framework for the scientific community, as it will deeply explore the use of different methodological approaches to infants' pressure data analysis. This is important as, in the context of developmental biomechanics, plantar pressure data captured in infancy have been processed according to adults' feet and habitual contact patterns, without considering the unique characteristics of infant feet and their ongoing development and focussing on low-resolution methodologies to analysis and interpretation of plantar pressures.

By undertaking this work, this chapter will establish an important step towards increasing the resolution of plantar pressure data processing and analysis in infancy. This would enable clinicians and researchers to ensure a solid and robust interpretation of the data, allowing considering foot function and its changes across infancy with more precision and objectivity, thereby improving knowledge of the typical biomechanics of the foot.

4.2. Comparison of two automatic masking approaches to analyse plantar pressure data in infancy

This section of chapter 4 has been submitted as a standalone manuscript to Gait and Posture and it is currently under review as:

Montagnani E., Morrison SC., Price C., (2022). Masking approaches to analyse plantar pressure data of new and confident walking infants. *Gait and Posture.*

I made the principle contribution in the conception and design of the study, analysis and interpretation of the research data and the drafting and critical revising of the final manuscript. Tables and figures are reported as in the paper but did not include analysis and interpretation of data from infants pulling up to stand.

Dated: 26.07.2022

Signed:

Eleonora Montagnani

4.2.1 Introduction

Masking analysis is the most common approach to quantification of plantar pressures in infancy and childhood (Bertsch et al., 2004, Bosch et al., 2010, Hallemans et al., 2003, Hennig and Rosenbaum, 1991, Dulai et al., 2021), as this is available within software packages, and data handling is straightforward. This approach also enables direct comparison of discrete values in regions of interest (ROI), which are automatically identified on the plantar surface of the foot, corresponding to precise anatomical areas.

Studies using regional analyses in infancy have reported the use of the "standard" masks, involving identification of heel, midfoot, forefoot and toe regions (Bosch et al., 2010, Bertsch et al., 2004, Hennig and Rosenbaum, 1991). Within the software used in these studies, the masks were created by implementing algorithms based on pre-defined criteria to identify ROIs (e.g., using typical foot proportions and consistent contact patterns of adults). Consequently, the manufacturer guidelines for the software used in the above works (Novel Scientific Medical, Germany) reported the definition of the heel and midfoot as 73% and 45% of the foot length from the toes to the heel respectively, whilst the forefoot and the toes were identified using pressure gradients around the peak pressures in these areas. Adopting a mask generated by algorithms based on adult foot proportions and contact patterns could limit the external validity of the data. For example, infants' feet present with different anatomical and morphological characteristics compared to adults, meaning that the standard algorithm is unlikely define ROIs correctly. Further, infants walking in self-selected directions are characterised by irregular foot shapes, dimensions and contact patterns, which can cause the presence of missing areas (e.g., toes, forefoot) (Price et al., 2017), undermining the ability of the standard algorithms to define regional boundaries. Accordingly, previous works have documented that the regions demonstrating higher pressure variability where the ones showing the lowest repeatability in adults (Gurney et al., 2008).

As an alternative, many software packages also offer the possibility of customising masks for processing data, allowing researchers to define ROIs across the plantar surface. This can be based on the specific foot proportions of the sample of interest, whilst still applying the mask automatically. As a result, the customisation of the mask allows researchers to adapt it to pressure steps that are highly variable and irregular in shape, dimension and spatial orientation. This customisation still facilitates an automatic application of the mask to each step, therefore maintaining an objective approach. Nevertheless, studies have not adopted a customised mask to automatically define plantar pressures in the early stages of walking development. A similar approach has been proposed to analyse a population of children aged between seven and 11 years of age (Cousins et al., 2012). Nevertheless, authors manually created the mask on a single foot (which they referred to as template), without justifying the approach against feet specific characteristics, for example, and then applied it to each feet included in the analysis. As a result, such approach not only lacked of justifications related to mask creation with respect to the sample of interest, but also implied that the mask created for a particular foot could be applied throughout the childhood without considering the ongoing foot development occurring from seven to 11 years of age.

Therefore, the aim of this work was to investigate the performance of two masking approaches, namely the standard and customised mask, to establish their appropriateness when used with respect to a plantar pressure data set of infants at early stages of walking development. This will be undertaken by considering: 1) the amount of variation present for each region when the two masks are applied and their differences 2) the successful masks application to the pressure steps. Through undertaking this work, internal consistency of the PhD will be assessed, which represents the basis to start from with the broader analysis.

4.2.2 Methods

Materials, methods, and ethical approval used in this section are reported in chapter 3, thus, a brief description will be reported hereafter.

4.2.2.1. Participants

Infants were eligible to take part in the study if they were not referred to or did not present at the time of the visit signs of musculoskeletal, neurological, visual, or auditory impairment, were born above the fourth percentile in weight and undertook testing within 21 days since milestone attainment.

4.2.2.2 Testing protocol

Testing was undertaken in a friendly, nursery style baby space at the University of Brighton, where pressure data was collected at the attainment of three different motor milestones, namely pull to stand (V1), onset of walking (V2) and confident walking (V3). Plantar pressure data was collected Novel EMED xl pressure platform (4 sensors per cm^2, 100 Hz).

4.2.2.3 Data processing

1. Pressure data extraction

Pressure data for both left and right feet were extracted as single files from the main pressure trials using the ‘define period tool’ in the standard EMED software (Novel, Munich, Germany). Next, pressure data within the selected frames was extracted singularly using the manual ‘select free line tool’ from the standard EMED software and saved in the form of maximum pressure pictures (MPPs). In each visit, MPPs were categorised based on the motor tasks performed by infants within each visit, as reported previously. In this section, MPP of infants pulling up to stand and supported standing were processed in combination, due to the small amount of pressure data present if the two tasks were separated. Only MPPs of trials of straight line walking were used for V2 and V3.

2. Masking analysis approaches

The literature (section 2.2.3) showed that the mask approach adopted more commonly in paediatrics is composed of five regions of interest (heel, midfoot, forefoot, hallux, and toes) (Bertsch et al., 2004; Bosch et al., 2010; Mesquita et al., 2018). However, this approach does not take into consideration the potential shifts in load from the medial to lateral side present infancy and childhood (Hennig and Rosenbaum, 1991; Alvarez et al., 2008), resulting in potential loss of information. Thus, dividing the foot regions in their medial and lateral sides has the potential to provide more insight into foot function development. Therefore, both regional approaches divided the foot in eight regions of interests: medial heel (MedH), lateral heel (LatH), medial midfoot (MedMF), lateral midfoot (LatMF), medial forefoot (MedFF), lateral forefoot (LatFF), medial toes (MedT), lateral toes (LatT) (Figure 7). Data processing for the two types of regional analysis were carried out as follow:

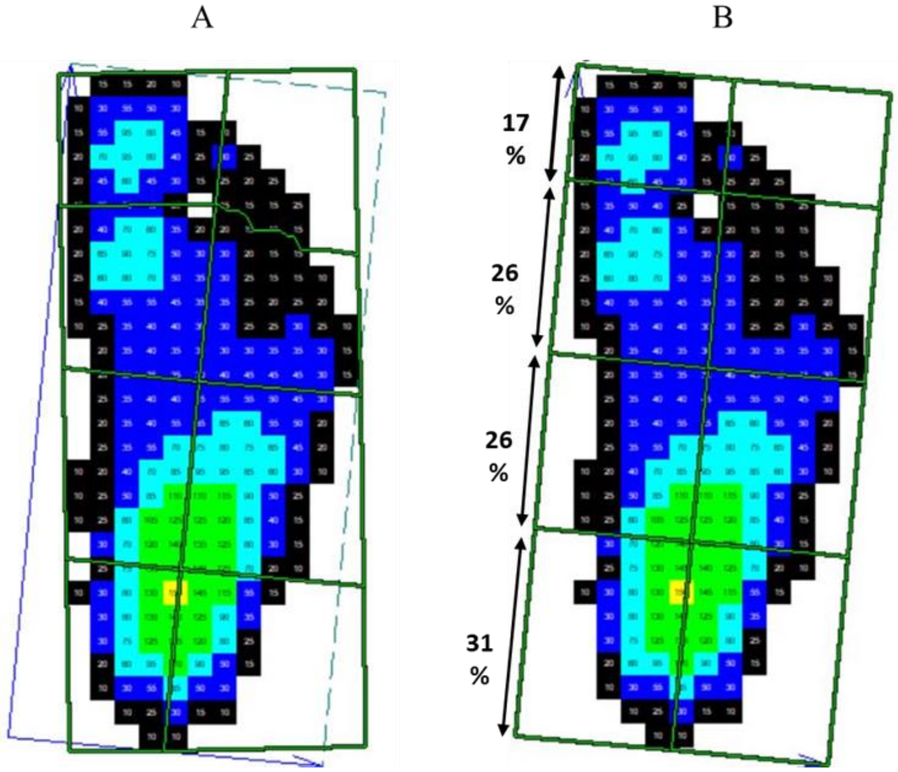
i. *The standard mask* was created using the Automask package (Novel, Germany), where the bisection mask command was selected to identify the medial and lateral ROIs. This mask identified the heel and the midfoot as 73% and 45% of the foot length from the toes to the heel respectively, and the forefoot and toe regions using pressure gradients around the peak pressures of these areas. Lateral and medial regions were defined within the software by a foot axis drawn from the centre of the heel to the centre of the second toe (Figure 9, A).
ii. *The customised mask* was implemented using the Automask package (Novel, Germany), where a percent mask was created (Figure 9, B). The proportions of each

ROI was based on radiographic images of typically developing infant populations that calculated the length of the calcaneus and first metatarsal bones (Paley et al., 2000, Segev et al., 2009). As the radiographic measures of the calcaneus suggested that it is the largest bones within the foot at these stages, the proportions of the heel region was calculated to cover the 31% of the foot length. The forefoot and midfoot both represented 26% of the total foot length, whilst the toes were estimated to cover 17%. The medial and lateral portions of each ROI were divided based on 50% of foot width, defined automatically as the axis passing from 50% of the toes to the heel. As anticipated, the data was expected to be highly variable both within and between infants, (Price et al., 2017), and therefore we decided to personalise the application of the customised mask. Accordingly, the mask was created on the pressure step that most closely matched the measured foot length at each walking stage (the step template). Then the mask was saved and applied to the entire data set of each infant at both stages of walking. This mirrored the approach of Cousins et al (Cousins et al., 2012), who manually created and applied a mask on a single foot that they identified as a within-children template.

With both approaches, steps were grouped for each participant at each walking stage using the Group Editor package (Novel, Germany), and peak pressure (PP) and contact area (CA) data were extracted for each step using the Group Mask Evaluation package (Novel, Germany). These variables were selected as they are commonly reported variables from plantar pressure studies in infancy, and also they would enhance comparison of masks application according to their specific measurement characteristics. PP represents a single sensor within a ROI, while CA accounts for the area covered a ROI, enabling the estimation of mask performance according to two different measures of plantar pressure data.

Unsuccessful mask application was defined visually by the lead researcher adopting two criteria: 1) the mask was not applied onto the step in full, 2) only some regions were successfully identified by the mask (e.g., only the heel, or heel and midfoot, etc.). Steps with unsuccessful mask application were excluded from the analysis and counted.

Figure 9. Example of regional analysis approaches using the hardware-generated mask (A) and the customised-automatic mask (B).



4.2.2.4 Data analysis

Pressure data was extracted in text format, managed with Microsoft Excel (Microsoft Office 2016), and then analysed using SPSS software (IBM Statistics, version 25). Analysis was conducted at three different levels:

i. *Variations:* For the eight ROIs selected in each visit, intra-individual coefficient of variation (CV) was calculated over the pressure values extracted according to the form:

$$CV = \frac{SD}{m} * 100$$

Equation 2. Calculation of Coefficient of Variation.

Where SD represent the standard deviation of the pressure and m is the sample mean. The use of CV allowed a direct comparison between the approaches and reduced the presence of outliers within the data. CV was calculated for PP and CA. These variables were chosen as they have been widely adopted in the field of paediatric plantar pressure analysis (Alvarez et al., 2008, Bertsch et al., 2004, Bosch et al., 2010, Müller et al., 2012). Data from each visit and each pressure variable was checked for normality using the Shapiro-Wilk test, which is most appropriate for small data sets (Ogunleye et al., 2018). Distribution of the data was not normal for the variables selected; therefore, comparison between the two masking approaches was carried out through calculation of Mann-Whitney Two Independent Samples test, in order to establish if data extracted with the customised mask was significantly different ($p<0.05$) from standard. The test was applied to each approach and at each visit for the respective ROIs and metrics selected (eight ROIs and two pressure variables).

ii. *Successful mask application:* This was expressed by reporting the percent of steps where masks application was unsuccessful, considering the total number of steps originally included in the analysis, to highlight the amount of data that can be lost with the application of two approaches.

4.2.3 Results

For this section, data from a convenient sample of 12 infants (5 females) have been analysed. These participants were selected as they were the first to complete data collection up to March 2020 at the University of Brighton, when the worldwide lockdown started due to the spread of Sars-Cov-2 pandemic. Demographics of the sample are reported in table 1. Seven left and six right feet were randomly selected, ensuring correspondences between visits, to maintain consistency with previous studies adopting regional analyses in infancy (Bertsch et al., 2004; Bosch et al., 2010; Hallemans et al., 2003; Hennig and Rosenbaum, 1991).

Table 1. Sample demographics of Chapter 4, section 4.2.

	Pull to stand (V1)				Onset of walking (V2)				Confident walking (V3)			
Measures	**Min**	**Mean**	**SD**	**Max**	**Min**	**Mean**	**SD**	**Max**	**Min**	**Mean**	**SD**	**Max**
Age at visit (months)	5.1	8.5	1.5	10.1	11.0	13.2	1.0	14.7	12.3	15.1	1.3	17.1
Age at milestone (months)	4.7	8.1	1.4	9.8	10.7	12.7	0.9	14.2	11.8	14.5	1.3	16.4
Days since milestone (days)	7.0	13.9	4.5	21	7.0	13.8	5.5	21.0	7.0	15.7	15.7	21.0
Mass (kg)	7.5	9.4	2.2	16.2	9.2	10.8	1.1	12.5	9.6	11.3	1.2	13.4
Height (cm)	65.4	70.7	1.8	74.5	71.5	75.5	2.8	81.1	71.9	77.8	3.6	83.3
Foot length (cm)	8.9	10.7	1.0	11.8	9.7	11.4	0.8	12.6	10.6	12.0	0.8	13.1
Foot width (cm)	4.6	5.2	0.5	11.8	4.4	5.4	0.4	5.9	4.3	5.4	0.5	6.2

4.2.3.1 Variation

Statistical comparisons of CV were reported within the clustered box plots for CA (Figure 10) and PP (Figure 11). In the figures, when the application of the customised mask (red boxes) was significantly different from the standard (blue boxes), differences are indicated with the star (*). With respect to CA, the only significant difference between data processed with the two masks at pull to stand was found at the lateral heel ($Z=-3.406$, $p=0.001$). Significant differences were found between the two approaches the onset of walking and confident walking in all the regions except in the lateral toes, where no significant differences have been detected in both V2 ($Z= -0.184$, $p=0.8540$) and in V3 ($Z= -1.562$, $p=0.118$). With respect to PP, there were no significant differences between the approaches at the three visits ($p \geq 0.05$). The only significant difference between standard and customised mask was found in confident walking in the lateral midfoot ($Z=-2.598$, $p=0.009$).

4.3.2.2 Successful mask application

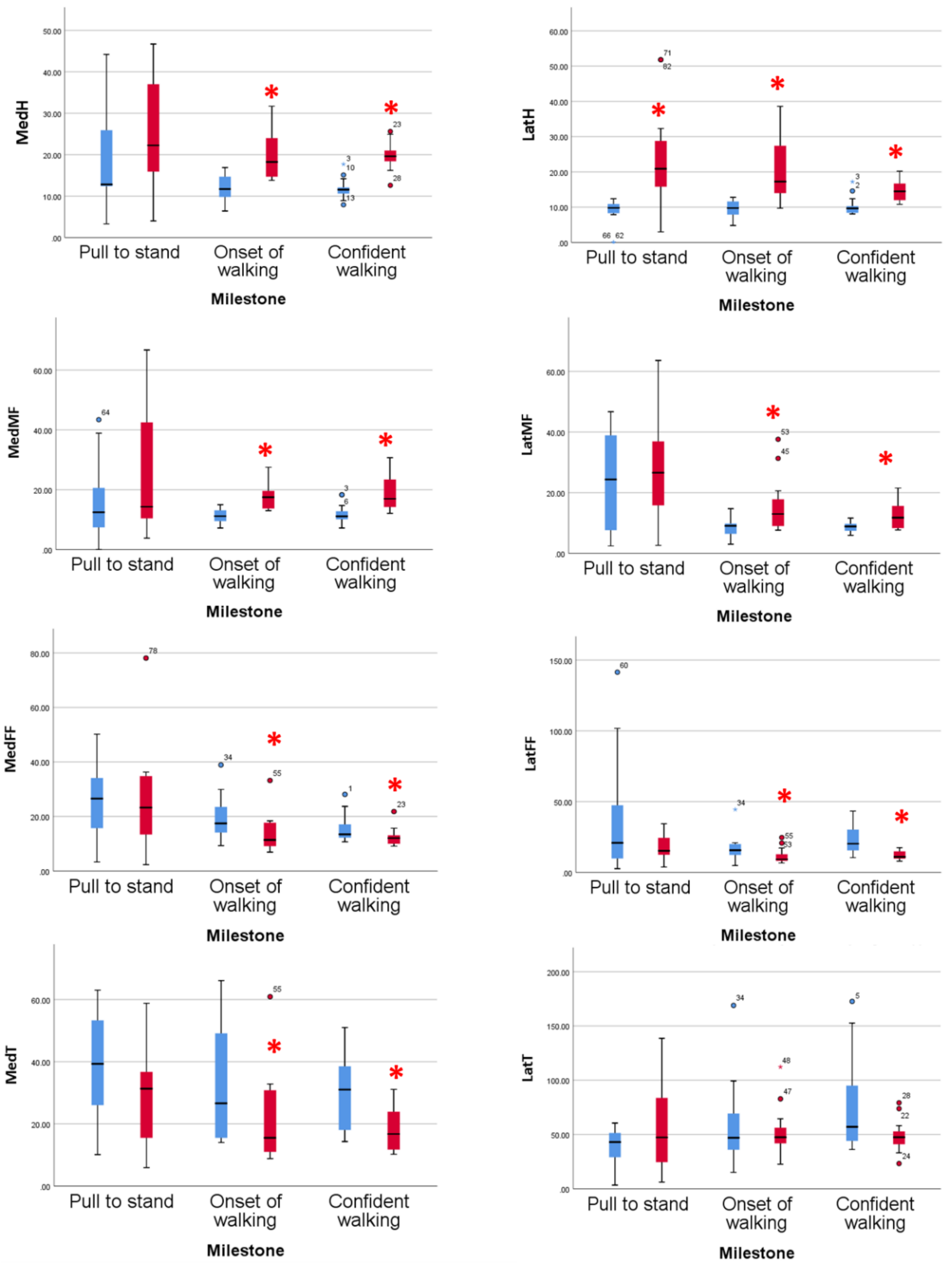
When the mask was applied to the MPPs, it has been found that, in both approaches, its application was unsuccessful in some instances. In Table 2, the optimal applicability was reported as number of MPPs where the mask was not applied correctly. Calculation of the percent of data loss was also reported with respect to the initial number of MPPs included in the analysis.

Table 2. Report of total amount of pressure data originally considered in the analysis (column 1), total amount of pressure data failed to be masked (column 2) and percent of data loss with respect to the amount of data initially included in the analysis (column 3), for both the standard and customised mask, respectively.

	Standard automatic mask			**Customised automatic mask**		
Milestone	**Total**	**Not masked**	**% of data loss**	**Total**	**Not masked**	**% of data loss**
Pull to stand	73	33	45.2	73	6	8.2
Onset of walking	255	56	22	255	4	1.6
Confident walking	536	143	27	536	0	-

As outlined in Table 2, the standard approach failed to mask a more consistent amount of data in comparison with the customised. The higher number of data loss is found in infants at pull to stand, where 45.2% of the data considered was unsuccessfully masked. Furthermore, out of 255 steps masked at the onset of walking, the standard mask was not applied to 56 steps (22% of data loss), whilst unsuccessful mask application with the customised mask was recorded for four steps (1.6% of data loss). In confident walking, the standard approach failed to mask 143 steps out of 536 (27% of data loss), whilst no data loss was reported when the customised was applied.

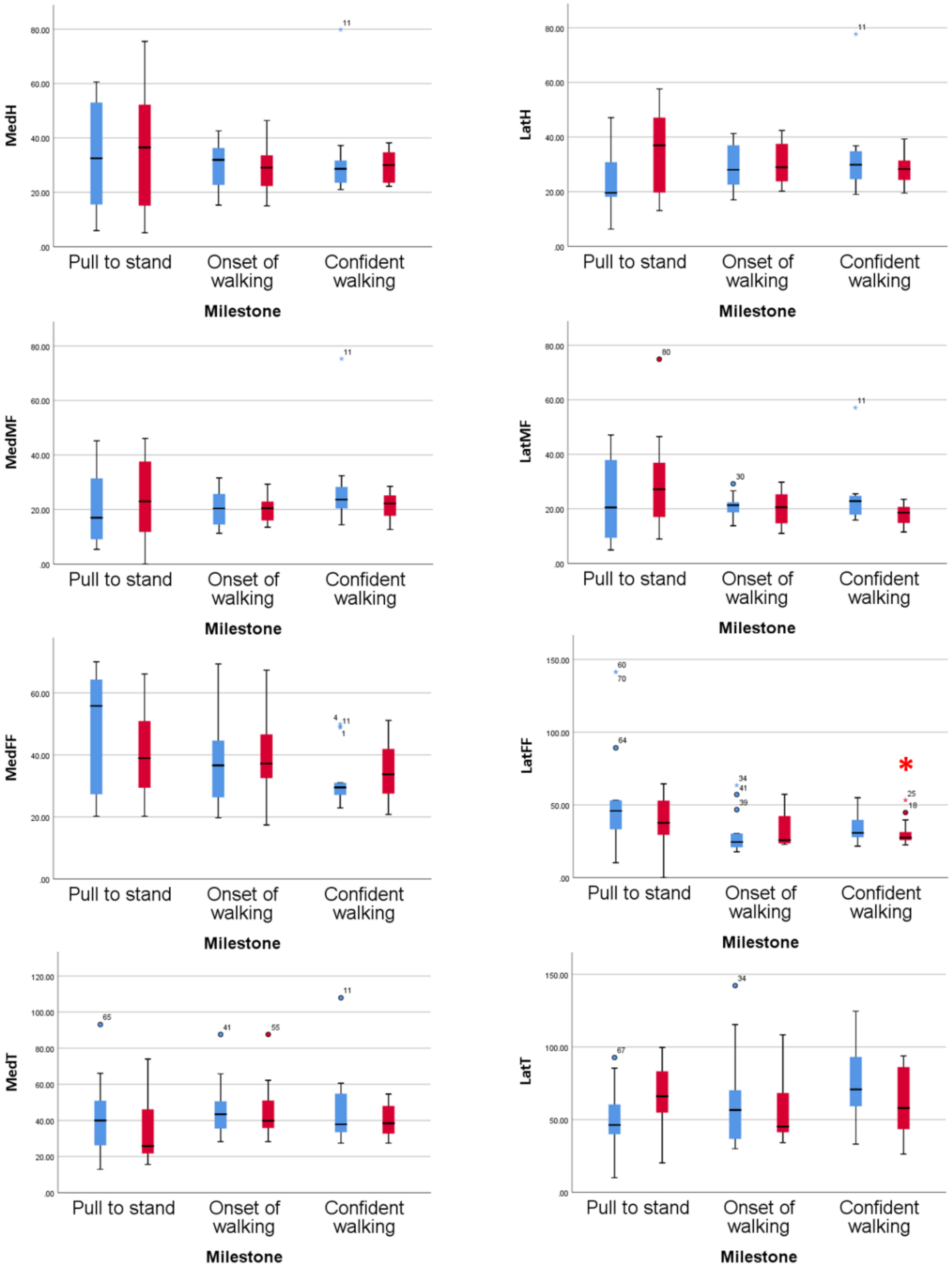
Figure 10. Box plot of intra-individual coefficient of variation (CV) in contact area.



[1]

[1] Boxes are clustered according to the visits analysed (X-axis). On the Y-axis, the CV is plotted. Blue and red boxes represent the variance of the standard and the customized masks, respectively. The red star indicates where the customized mask significantly differ from the standard mask.

Figure 11. Box plot of intra-individual coefficient of variation (CV) in peak pressure.



[2]

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[2] Boxes are clustered according to the visits analysed (X-axis). On the Y-axis, the CV is plotted. Blue and red boxes represent the variance of the standard and the customized masks, respectively. The red star indicates where the customized mask significantly differ from the standard mask.

4.2.4 Discussion

This study aimed to assess the performance of two different masking approaches, namely the standard and costumised masks when applied to plantar pressure data of infants in early stages of motor development. This work sought to understand if the customised mask could yield an improved performance, hence constitute a more appropriate approach than the standard mask for processing infants' plantar pressure data.

One principle we used to assess masking performance was to consider the applications of both masks to the infants' plantar pressure steps, and to check how frequently these failed. In instances where the mask could not be applied, this would reflect a mask that could not adapt to the highly variable infants' steps made in self-selected directions, and would lead to step exclusion and data loss. We found that the customised mask scaled to infants' feet led to a more successful application compared to the standard mask in all three stages of motor development. As anticipated above, the challenges with the standard mask application were likely due to inter-variability in shape, dimensions and contact patterns of the infants' steps. Whilst we demonstrated that using a customised mask mitigates data loss, we also assume that personalising the customised mask application for each infant and motor stage is an important factor leading to a more successful result, allowing us to address the presence of within-infant variability in such a data set (Price et al., 2017). Being aware of the limitations related to successful mask application is important in research of this field, as it can inform the amount of data that would be necessary to obtain a sufficient sample. This means that in the case of dealing with plantar pressure data captured from infants performing self-selected motor tasks, researchers should be aware that the standard masking approach led to more steps being lost from analysis.

Another assessment of performance was to calculate the variation across individual steps and compare this between the two masks applied for CA and PP. In the work by Giacomozzi and Stebbins (2017), the authors considered the absence of significant differences between the variation of the two masking approaches as an estimate of the appropriateness of mask performance. For example, whilst the lateral forefoot was the only region demonstrating significant differences in variation for PP between masks, we found that for CA, the customised approach demonstrated significantly different results compared to the standard mask, in all regions except in the lateral toes. The differences of CA outputs between approaches might be explained by a combination of factors. First, the standard masks adopted in previous work (Bosch et al., 2010; Bertsch et al., 2004; Hennig and Rosenbaum, 1991) were based on algorithms that have been created using consistent foot proportions and typical contact patterns in adults. Alternatively, the customised mask of this study has been implemented to retain specific infants' feet proportions, resulting in quantification of different areas covered by the ROIs, as the two masks use different criteria to divide the plantar surface. Second, the CA was measured using all the pixels present in a specific region, whilst PP data relied on just the pixel with the highest pressure among the number in that region. Thus, it is possible to say that CA values are more sensitive to masking approaches than PP.

As anticipated, the strengths of the masking approaches would lie within the ability to define regions more consistently across participants. A consistent identification of the regions from the approaches means that the inter-individual variability of the data set would not have an influence on the mask application. Accordingly, it has been found that the customised mask demonstrated larger coefficients of variation in output, particularly for CA, compared to the standard mask (Figure 10), which would define an inconsistent mask application. However, it is important to highlight that the application of the standard mask led to more unsuccessful applications to the steps, which caused the removal of more data from the analysis for all the three motor stages considered in this study. By processing a smaller volume of data with the standard mask (Table 2), steps that were more variable were excluded as part of the sample rather than including them. Hence, the lower coefficients of variation in PP and CA demonstrated by the standard mask do not reflect its more efficient performance and justify its use. Rather, the coefficients of variation being higher in the customised mask are positive representations of performance in this instance, as they reflect the capability of such a mask to process the data that was collected almost in full.

4.2.5 Limitations of the study

Some limitations are present within this study. First, at each of the visits analysed, a different amount of data have been included in the analysis, given the different abilities of infants to perform the tasks. For example, if we consider infants at pull to stand, the amount of pressure data was considerably reduced than the stages of walking due to the nature of the tasks performed as well as infants' motor abilities. Therefore, comparing the application of the customised mask between the visits has to be done cautiously, considering that the statistical analysis might have been limited due to the different number of data in each visit. Moreover, it is important to highlight that pressure data at pull to stand were a mix of two motor tasks (standing supported and pull to stand records) and those are different from walking stages. Therefore, the application of the customised mask on infants at pull to stand is not exclusive of one motor task, as it occurs with the other two visits.

4.2.6 Conclusion and thesis indication

The customised mask and its personalised application to a data set of infants at different stages of motor development allowed us to retain nearly all the plantar pressure steps collected at pull to stand, onset of walking and confident walking. The differences in performance compared to the standard mask were related to the area of contact, likely due to the presence of different criteria that have been used to identify regions of the masks. The analysis of plantar pressure data in early motor stages could therefore benefit from a masking approach implemented using criteria based on specific proportions of infants' feet. Consequently, the customised mask proposed in this work can be considered as an appropriate alternative to the standard mask for the quantification of plantar pressure in this sample of infants. Such an approach could therefore be considered for other pressure analyses, where data sets of highly variable plantar pressure are present. This has the potential to enhancing a more robust analysis and improving data interpretation in future works as well as in this thesis.

4.3. Pedobarographic statistical parametric mapping of plantar pressure data in new and confident walking infants: a preliminary analysis

This section of chapter 4 is a co-authored paper that has been re-formatted for this thesis. The bibliographic details of this co-authored paper including all authors are:

Montagnani E., Morrison SC., Varga M., Price C. (2021). Pedobarographic Statistical Parametric Mapping of plantar pressure data in new and confident walking infants: a preliminary analysis. *Journal of Biomechanics*.

DOI: http://doi.org/10/1016/j.jbiomech.2021.110757

I made the principle contribution in the conception and design of the study, analysis and interpretation of the research data and the drafting and critical revising of the final manuscript. Figures in this section of the thesis are reported exactly as in the paper.

Dated: 26.07.2022

Signed:

Eleonora Montagnani

4.3.1 Introduction

The customised mask demonstrated to be an appropriate approach to analyse infants' data, using criteria based on specific foot proportions of infants to identify regions of interests (ROI), hence constituting a more precise and accurate methodology than the standard mask. Regardless the type of masking approach adopted, it is important to recognise that regional analysis software has been developed to be user-friendly and accessible to researchers and clinicians without the need to understand particular statistics packages or programming languages (e.g., Matlab, Python). These characteristics made regional analysis easy to implement for pressure data processing, which is why it has been extensively used throughout the years. This ease in obtaining and processing data, however, comes with certain disadvantages, notably assumptions relating to the statistical treatment of regional data as discrete, treating the regions of the foot independently (Pataky and Goulermas, 2008). In fact, this approach assumes that pressure is discrete and not continuously distributed across the plantar surface of the foot, thereby providing a low-resolution method to analyse pressure data, which can affect interpretation. In addition, the use of regional analysis in infancy presents limitations due to the ongoing foot development, which causes lack of clear anatomical definition on the plantar surface and a lack of hypotheses relating to the ROIs typically analysed in the plantar pressure field.

As opposed to regional analysis, pedobarographic Statistical Parametric Mapping (pSPM) is a continuous analysis that conducts statistical inference at the pixel level in the spatial domain. This approach increases the resolution of data analysis by mitigating the risk of statistical bias, data processing inconsistencies and enhancing accurate pressure data interpretations (Pataky and Goulermas, 2008). pSPM has been adopted already in adults (Booth et al., 2018, McClymont et al., 2016, Oliveira et al., 2010, Pataky et al., 2008b) and children (Phethean et al., 2014). However, the use of pSPM in infants' pressure analysis has not been reported. Adopting pSPM could be non-trivial in infancy, as a regular foot profile on the pressure platform could be influenced by a combination of a variety of factors such as high gait variability, the testing protocol adopted, and the developmental characteristics of the infant's feet. Consequently, the presence of atypical foot placements onto the pressure platform could lead to capturing MPPs highly irregular in shape and spatial orientation (Price et al., 2017) that could make data processing challenging. Therefore, this section of the thesis aimed to detail the implementation of the pSPM processing framework on infants' pressure data. By undertaking this work, initial comparison of pressure patterns between infants at the onset of walking and confidently walking was also reported, providing a preliminary set of novel information about plantar pressure patterns that could direct future research in the field as well as in this thesis.

4.3.2 Methods

As for the previous section, materials, methods, and ethical approval used in this section are reported in chapter 3.

4.3.2.1. Participants

Infants were eligible to take part in the study if they were not referred to or did not present at the time of the visit signs of musculoskeletal, neurological, visual, or auditory impairment, were born above the 4th percentile in weight and undertook testing within 21 days since milestone attainment.

4.3.2.2 Testing protocol

Testing was undertaken in a friendly, nursery style baby space at the University of Brighton, where pressure data was collected at the attainment of three different motor milestones, namely pull to stand (V1), onset of walking (V2) and confident walking (V3). Plantar pressure data was collected Novel EMED xl pressure platform (4 sensors per cm^2, 100 Hz). As opposed to the previous study however, this work only considered data from trials of walking made in straight lines of V2 and V3, as statistical comparison was performed on data that represent the same task. Therefore, trials of V1 will not be used in the present work.

4.3.2.3 Data processing

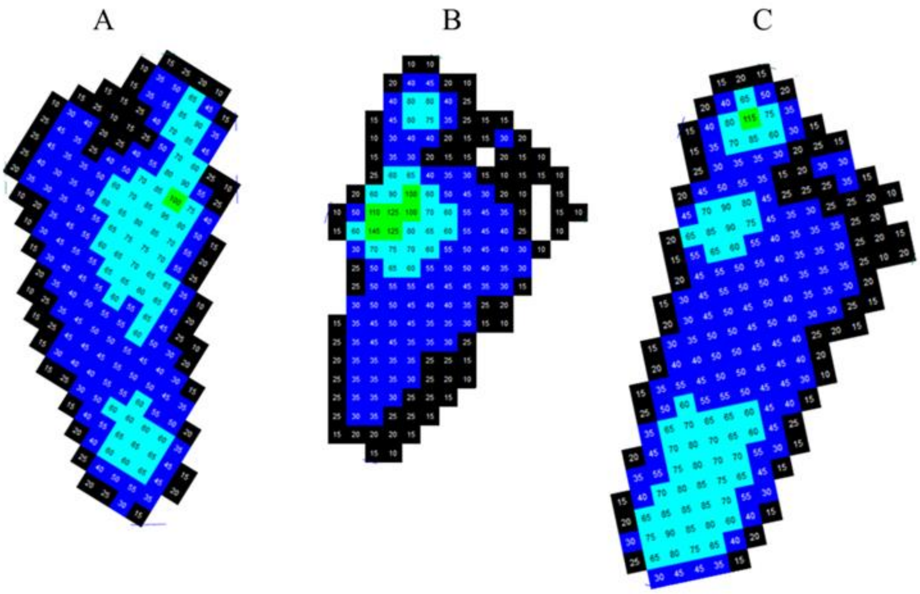
1. Pressure data extraction

Steps were extracted from the walking trials of V2 and V3 using the ‘define period tool’ in the standard EMED software (Novel, Munich, Germany). Subsequently, each step within the selected frames was extracted singularly using the manual ‘select free line tool’ from the standard EMED software and saved.

2. pSPM processing data framework

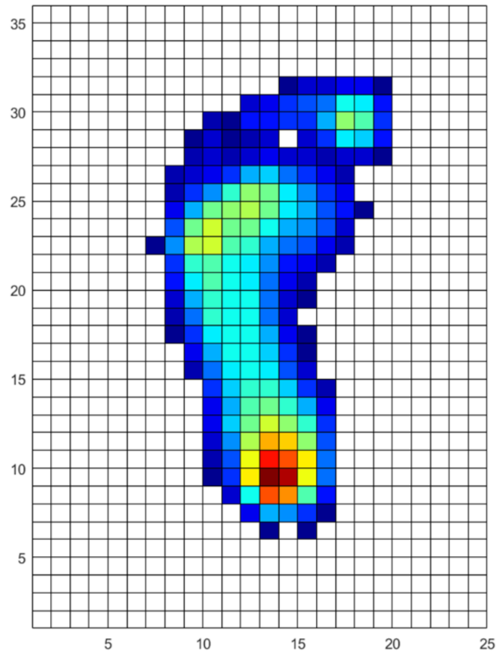
Steps were processed if the feet were within the platform borders and did not miss extensive anatomical parts. For example, steps made only with the forefoot or heel and midfoot were not considered for processing (Figure 12).

Figure 12. Example of steps made only with the forefoot and midfoot (A) and with the forefoot (B) compared to a full step (C).



A visual inspection of the stance phase of each step was also carried out to ensure processing of steps from full walking cycles. This was necessary due to the diverse nature of foot contact at the two visits. Left and right feet were processed and analysed separately for both V2 and V3. This was made according to previous studies adopting pSPM (Pataky et al., 2008; Booth et al., 2018; Phethean et al., 2014), which reported analysis of both feet as opposed to one foot only. Maximum pressure pictures (MPPs) of the steps were exported as ASCII text files (Novel Emascii software), and imported into Matlab 2019a (The Mathworks Inc, Natick, USA) as 2-dimensional (2D) numeric matrices for data processing and analysis. Each MPP was then positioned in a grid of 36x25 pixels (Figure 13), to standardize matrix dimensions of each MPP and create a common reference system. Non-zero entries of the MPP matrices corresponded to pixels containing pressure values.

Figure 13. Example of maximum pressure picture (MPP) positioned in the 36x25 grid of pixels.



i. *Transformation of pixels to point cloud*

The traditional data processing mentioned elsewhere (Pataky and Goulermas, 2008) for MPPs analysis was modified in this section. Specifically, MPPs were transformed into point clouds, defined as sets of points in a space, containing sets of x, y, and z coordinates. To perform this transformation, the coordinates of the pixels in the matrices' reference system were used to represent the pixels in the 2-dimensional (2D) Euclidian space. Such representation was used to convert MPPs into point clouds using a built-in Matlab function ("pointcloud") that transformed each pixel into a point, whilst pressure values within each pixel were stored in separate vectors. This was done to use point coordinates of the point clouds as determinant feature for the further phases of data registration, instead of the pressure values. Therefore, this approach enabled to retain original geometric characteristics of the infants' feet, excluding pressure values in the registration processes. Accordingly, the high variability in pressure might have affected intensity-based registration algorithms, reducing data quality processing, and influencing further data interpretation.

ii. *Point cloud registration*

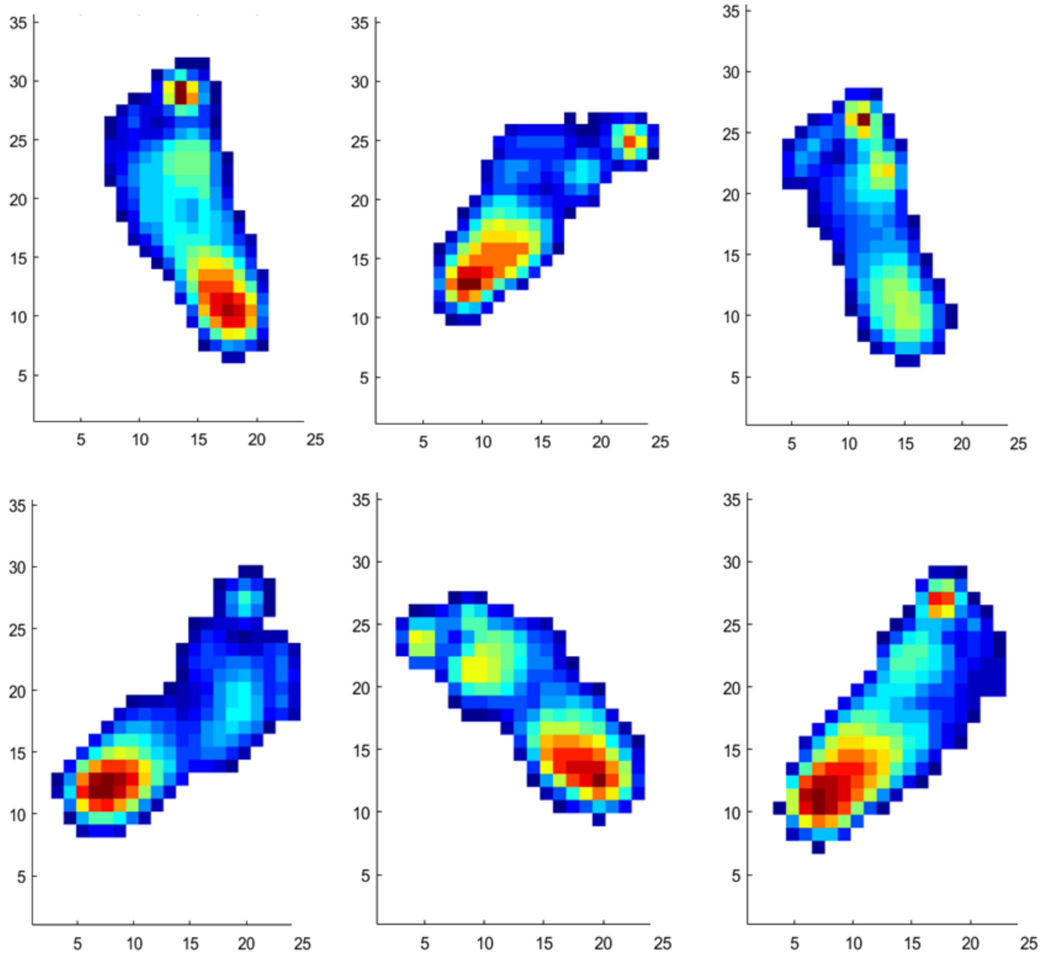
Once MPPs were transformed to point clouds, registration could be performed. Registration is defined as the process that allow transformation of the MPPs or point clouds, so that homologous structure can align optimally in their spatial dimension (Pataky and Goulermas, 2008). According to previous research, point clouds were registered within and between infants (Phethean et al., 2014; Booth et al., 2018).

iii. Within-infant registration

At each of the two visits, point clouds were spatially aligned within infant and within feet. A source and a template were used for this purpose. A source is defined as the transformed point cloud whereas the template is the point cloud onto which the transformed point cloud are registered (Pataky et al., 2008). To perform within-infant registration, a template per infant per foot was arbitrarily chosen at both visits, being the one with the highest number of points (that corresponded to the highest number of pixels). After the template was identified for each infant, within-infant registration was performed.

For this purpose, previous literature adopted rigid body transformation, which allowed translation and rotation of the pressure images (Pataky and Goulermas, 2008; Phethean et al., 2014). In the case of the present data, rigid registration was performed with the iterative closest point (ICP) algorithm, considered as the most well-known and performing algorithm to accomplish 2D point clouds transformation (Yang et al., 2015). However, the visual inspection of the data highlighted highly variable shape, size and spatial orientation of the left and right pressure images within infants (Figure 14). The ICP algorithm is highly susceptible to local minima and its performance relies on the quality of the initial pose of the point clouds (Yang et al., 2015). For this reason, previous works has tried to improve its implementation by performing initial coarse alignment of the data (Makadia et al., 2006, Rusu et al., 2009). Therefore, an additional data processing passage was required prior to within-infant registration, to yield optimal points overlap. This was obtained by vertically aligning the original MPPs using principal component analysis (PCA), similarly to Kim et al. (2013).

Figure 14. Example of intra-infant variability of orientation, shape and size of both left and right pressure images.



iv. Computing axes of maximum pressure pictures with principal components analysis

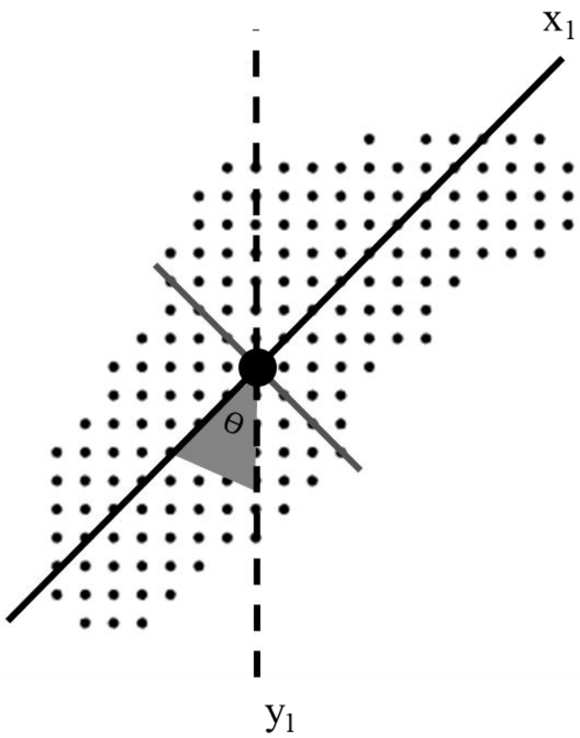
As first, binary images of each MPP were created by replacing all pixels containing pressure values with ones and setting all other values to zeros, using a built-in Matlab function (“imbinarize”). The matrices of each binary images were then vectorised in *a* and *b* dimensions, where *a* and *b* had the same number of indices and expressed the coordinates of binary images in space. The mean of *a* and *b* was then calculated and subtracted to each index of the respective coordinates, resulting in two new vectors: A and B. This reduced the mean square error of approximating the data and finding the centroid of the images. Coordinates were then positioned in a *2xm* matrix, where m indicates the number of indices of the coordinates, and the covariance matrix was calculated according to:

$$C = \begin{pmatrix} \text{cov}\,(A, A) & \text{cov}\,(A, B) \\ \text{cov}(B, A) & \text{cov}\,(B, B) \end{pmatrix}$$

Equation 3. Covariance matrix.

This enabled to obtain both the spread (variance) and the form of relationship (covariance) of our data, hence the type orientation of the images in the space (feet oriented towards left or right in the plane). Once the covariance matrix was calculated, eigenvectors and eigenvalues of the covariance matrix were found. Given the covariance matrix, eigenvectors are vectors of the matrix pointing in the direction of the orientation of the data. Eigenvectors are associated to eigenvalues, which contain information about their magnitude. For the present data, pairs of eigenvectors of the binary images were found and sorted in decreasing order. This enabled the choice of the largest and smallest eigenvectors, being the principal components of the covariance matrix. Once eigenvectors were identified, they were plotted as the major axes of the images (Figure 15) and principal component analysis (PCA) was conducted.

Figure 15. Non-aligned binary image (black dots), principal axes are identified as black (x_1) and grey lines intersecting at the image centroid, where the vector parallel to the y-axis passes through (y_1).



[3]

For the present work, the use of eigenvectors was essential as they represent the fixed axes around which images can be rotated. Specifically, feet were vertically aligned based on their major axes through a linear transformation.

In order to perform rotation of the images, Θ was calculated as the angle forming between the longest axis (x_1) and the vector parallel (black dashed line) to the y-axis passing through the centroid (y_1) (Figure 13), according to the form:

$$\theta = \text{atan}(x_1, y_1)$$

Equation 4. Calculation of θ.

Where "atan" is a built-in Matlab function returning the inverse tangent ($\tan^{-1}$) of the ratio of x and y in radians, with x and y being the coordinates expressed as covariance. Once Θ

[3] x_1 and y_1 were used to calculate Θ. The grey, shorter axis was reported for display purposes, enabling to visualize the centroid of the image, thus the intersecting point of y_1.

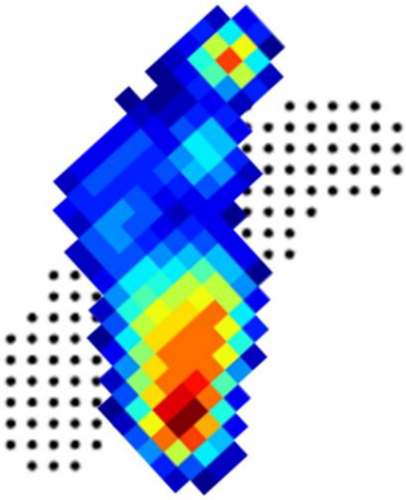
was calculated (Equation 4), it was applied in the rotational transformation matrix (Equation 5), having the general form:

$$R = \begin{pmatrix} \cos\Theta & -\sin\Theta \\ \sin\Theta & \cos\Theta \end{pmatrix}$$

Equation 5. Rotational transformation matrix.

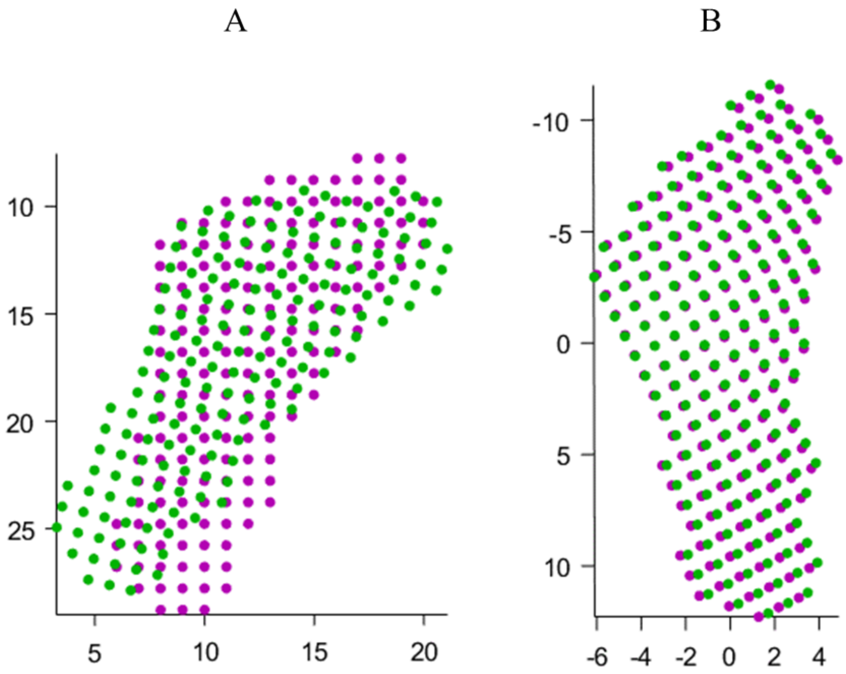
This enabled to create the transformation matrix to perform a counter-clockwise rotation of the images to vertical. The coordinates were then multiplied by the transformation matrix, thus obtaining vertically aligned feet (Figure 16).

Figure 16. Non-aligned binary image (black dots) and vertically aligned maximum pressure picture (MPP).



Once PCA was performed, the rotated binary images were re-transformed to point clouds, and within-infant registration was achieved through the rigid ICP algorithm. Quality of the registration pre and post PCA is also reported (Figure 17).

Figure 17. Visual representation of overlap between template (pink points) and the source (green points) during within infant registration performed without principal component analysis (A) and with principal component analysis (B).



After within-infant registration, for each vertex of the template a built-in Matlab function was used based on Euclidean distances ("findNearestNeighbour") that returns the nearest neighbours of a query point in the input point cloud, to find corresponding points between the sources and the within-infant template.

v. *Morphological averaging*

Once aligned and registered, corresponding coordinates of point clouds were averaged in a custom-written Matlab script, resulting in one mean point cloud per participant per foot (Phethean et al., 2014). This was performed to reduce the impact of differences in shape and dimensions of the point clouds (Figure 12), and to enhance further steps of data processing.

vi. *Between-infants registration and template computation*

As opposed to within-infants registration, this phase of work transforms all the point clouds to a between-infant template so that anatomically corresponding points optimally overlap.

To achieve this, the non-rigid coherent point drift (CPD) algorithm was adopted for point cloud registration, to allow the shape of the point clouds to change using a displacement field as transformation.

Differently from the within-infant template, a between-infants template was chosen from data set as the point cloud with length and width closest to the mean length and width of all the within-infant mean point clouds (Pataky et al., 2011). This template was referred to as unbiased because, according to the definition of central tendency, it constituted an unbiased approximation required to deform a participant foot to the mean of the entire population (Pataky et al., 2011). This template was not computed also for the within-infant registration, as it was assumed that length and width of the feet of the same population were similar. Nevertheless, the application accuracy of this unbiased between-infants template was validated against an arbitrary between-infants template, chosen as the point cloud with the highest number of points (pixels). Application of both template was reported in the figures below, and their validation was demonstrated by calculating root mean square errors (RMSE) according to:

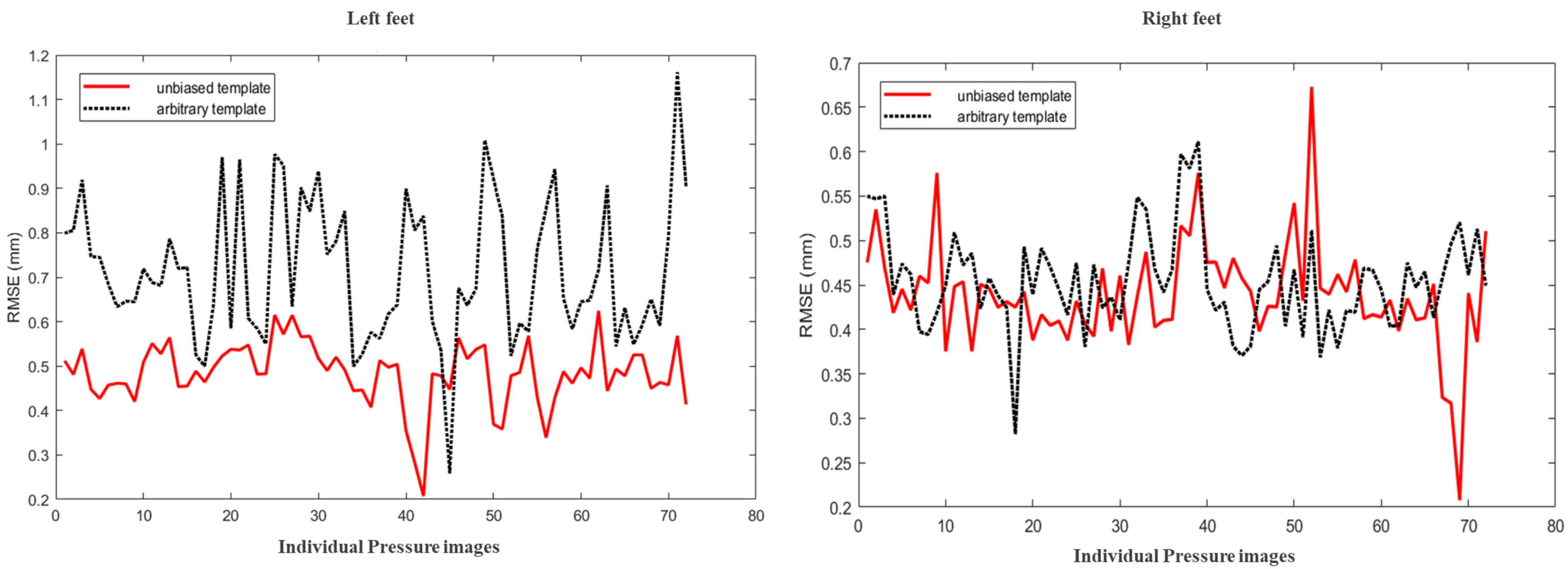
$$\mathrm{RMSE} = \sqrt{\frac{1}{\mathrm{N}} \sum_{\mathrm{i}=1}^{\mathrm{N}} (\min_{\mathrm{x} \in \mathrm{S}} \|\mathrm{y_i} - \mathrm{x}\|2)^2}$$

Equation 6. Calculation of the root mean square error (RMSE).

As the Euclidean distance for each coordinate point ($y_1 \ldots y_N$) between the surface *S* of the between-infants templates (both unbiased and arbitrary) and the individual point clouds of each infant at the onset of walking and confident walking. The accuracy of both templates to perform the between-infants registration with the CPD algorithm on both left and right feet was reported in the two figures below (Figure 18). Because the unbiased template showed the lowest RMSEs values from the between-infants registration on the individual pressure images in both feet, it was chosen as the official between-infants template as opposed to the arbitrary.

As after within-infant registration, for each vertex of the template a built-in Matlab function for point clouds (“findNearestNeighbour”) was used, based on Euclidean distances, which returned the nearest neighbours of a query point in the input point cloud.

Figure 18. Accuracy of the unbiased (red line) and arbitrary (black dotted line) between-infants templates of right and left pressure images of infants at the onset of walking and confident walking.



[4]

[4] The arbitrary template was chosen considering the pressure image with the higher number of pixels.

4.3.2.4 Data analysis

Analysis of the data was performed on different levels. First, to determine the quality of the within and between-infants registration algorithms, the RMSE was calculated between the sources and the template (Pataky, 2012) for each MPP, according to equation 6. This allowed descriptive evaluation of the Euclidean distances between corresponding points of the sources within the template in the respective registrations. RMSE was calculated within the registration algorithms in a custom-written Matlab script. The RMSE measurement unit were then transformed in order to obtain values in mm rather than in the unit of the platform sensors. The mean and standard deviation (SD) of the RMSE of all the MPPs were calculated and reported. The RMSEs representing the overlap of the template to itself was deleted as it would give zero values due to the perfect overlap. Graphic representations of the application of both registration algorithms were also reported, in order to qualitatively appreciate their performance on the present data set.

Analysis with SPM1D was conducted between sets of point clouds of V2 and V3. The use of SPM1D data on 2D pressure data was possible as pressure data was spatially aligned and nonparametric inference used (Pataky and Goulermas, 2008). Analysis was conducted using a two-tailed, nonparametric paired sample SPM1D t-test (http://www.spm1d.org/), with significance set as $\alpha=0.05$. A t-value was calculated at each point of the point clouds, defining an SPM t-curve. As nonparametric inference was used, multiple comparison corrections was performed using nonparametric permutation test, where the critical threshold was based on the maximum test statistic value across the entire domain (Pataky, 2012). If the SPM t-curve crossed this critical threshold (t critical) at any point, significant points were located (Pataky, 2012), reflecting that pressure in those points is significantly different between V2 and V3. However, SPM1D only supports critical test statistic calculation, thus cluster-specific p values were not available.

4.3.3 Results

As for section 4.2, pressure data of 12 infants were analysed in this work as part of the University of Brighton sample. Demographics of the sample were reported in table 3. Three steps for each foot, for each participant at both visit were used for this work (3 steps*2 feet*12 participants*2 stages, n=144).

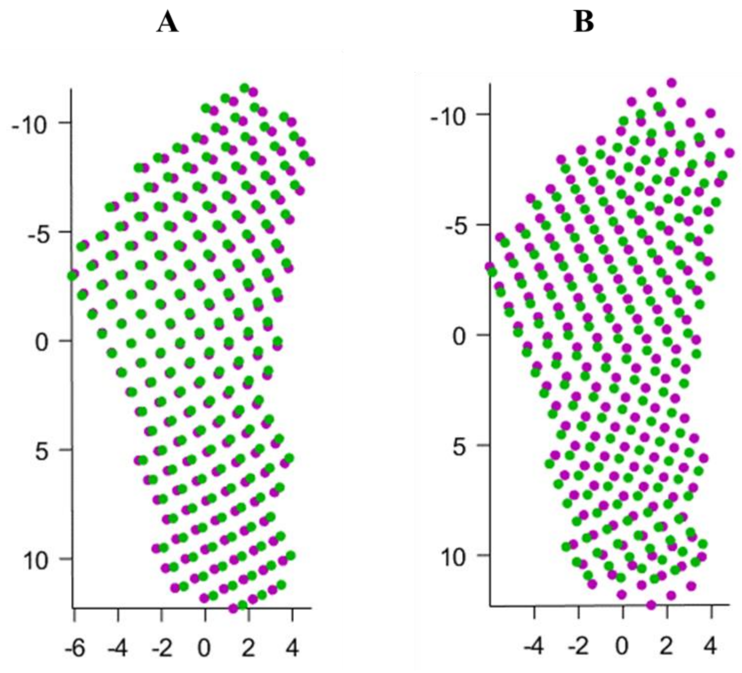
Table 3. Sample demographics of chapter 4, section 4.3.

	Onset of walking (V2)				**Confident walking (V3)**			
Measures	**Min**	**Mean**	**SD**	**Max**	**Min**	**Mean**	**SD**	**Max**
Age at visit (months)	11.0	13.2	1.0	14.7	12.3	15.1	1.3	17.1
Age at milestone (months)	10.7	12.7	0.9	14.2	11.8	14.5	1.3	16.4
Days since milestone (days)	7.0	13.8	5.5	21.0	7.0	15.7	15.7	21.0
Mass (kg)	9.2	10.8	1.1	12.5	9.6	11.3	1.2	13.4
Height (cm)	71.5	75.5	2.8	81.1	71.9	77.8	3.6	83.3
Foot length (cm)	9.7	11.4	0.8	12.6	10.6	12.0	0.8	13.1
Foot width (cm)	4.4	5.4	0.4	5.9	4.3	5.4	0.5	6.2

4.3.3.1 Within and between-infants registration quality

With respect to registration accuracy, the mean and SD RMSEs in the left feet were 0.36 mm (0.09) and 0.39 mm (0.08) for within and between-infant registration, respectively. In the right feet, the mean and SD RMSEs were 0.38 mm (0.06) and 0.37 mm (0.05) for within and between infants registration, respectively. Visual representation of the registration performances was also presented in figure 19. Specifically, figure 19 (A) demonstrated minimal non-overlapping points found on the posterior border of the heel and the medial border of the hallux. Considering the between-infants registration, non-overlapping points were present around the apex of the toes, around the foot periphery and between the heel and the midfoot (Figure 19, B).

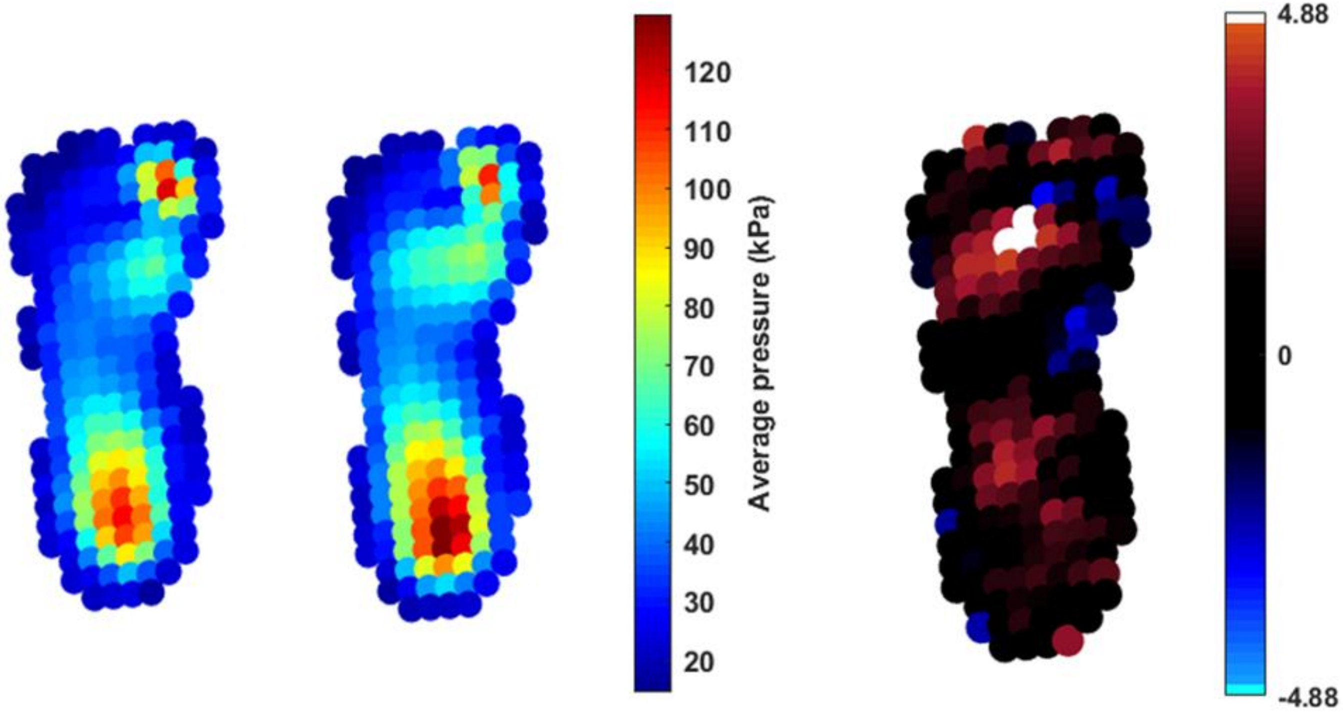
Figure 19. Visual representation of the source (pink points) and template (green points) overlap during within-subject registration (A) and between-subjects registration (B).



4.3.3.2 Plantar pressure inference

In the transition from new to confident walking, analysis with pSPM detected a cluster of significantly increasing pressure in the central forefoot of the left foot (Figure 20). Statistically significant differences in pressures were not identified in the right foot; however, the qualitative trends suggested the presence of changes in pressure (Figure 21). Specifically, in both left and right feet, the average pressure distribution of the two stages of foot loading showed that pressure increased in the central heel, medial to lateral forefoot and decreased in the hallux.

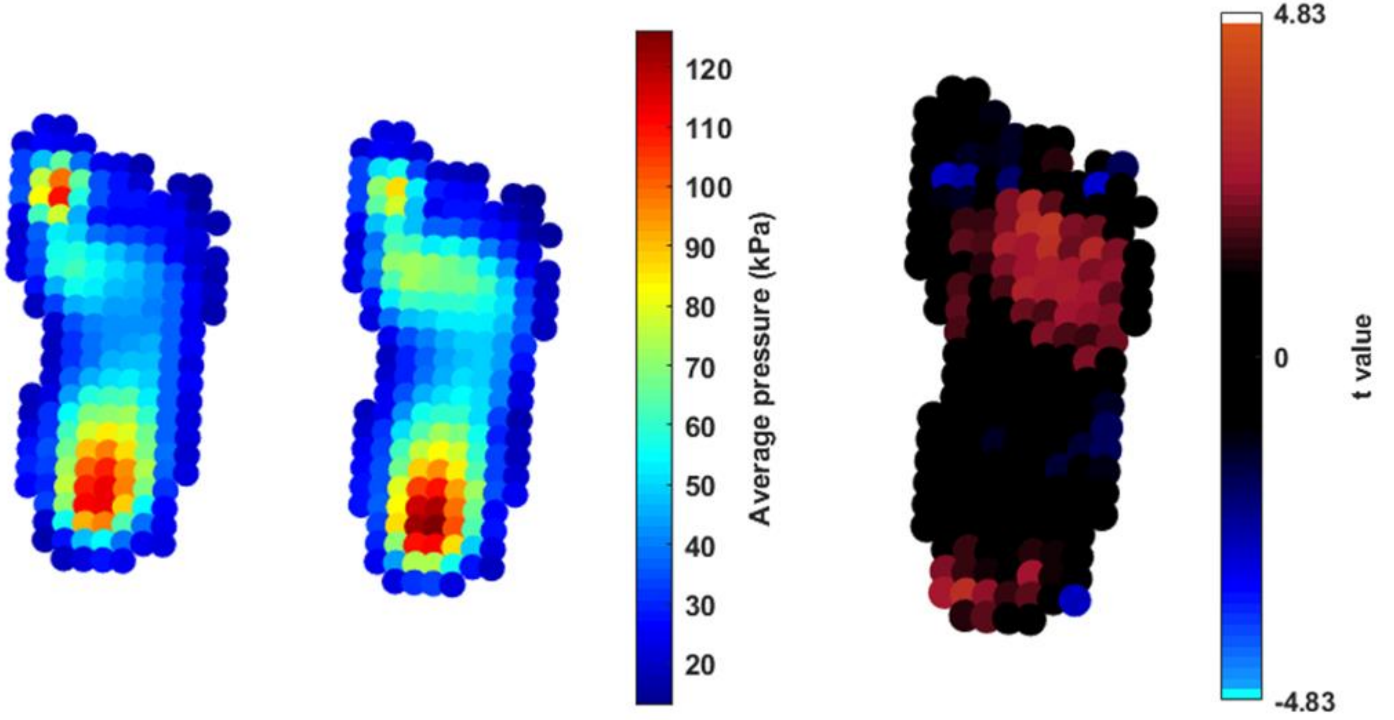
Figure 20. Nonparametric pSPM paired t test on left feet comparing V2 and V3. From left to right: average pressure distribution of V2, average pressure distribution of V3, and raw t value of statistical analysis. White points indicate detection of significantly increasing pressure.



[5]

[5] The extremes of the colourbar in the inference image (extreme right) reflects t-values needed to reach statistical significance, with alpha set at 0.05. The colourbar for the average pressure distribution images presented different min and max kPa values that were adjusted by the overall max and min values to allow for comparison. Cool and warm colours identify where maximum pressure pictures (MPP) of confident walking infants had lower and higher peak pressure than new walkers, respectively.

Figure 21. Nonparametric pSPM paired t test on left feet comparing V2 and V3. From left to right: average pressure distribution of V2, average pressure distribution of V3, and raw t value of statistical analysis.



[6]

[6] The extremes of the colourbar in the inference image (extreme right) reflects t-values needed to reach statistical significance, with alpha set at 0.05. The colourbar for the average pressure distribution images presented different min and max kPa values that were adjusted by the overall max and min values to allow for comparison. Cool and warm colours identify where maximum pressure pictures (MPP) of confident walking infants had lower and higher peak pressure than new walkers, respectively.

4.3.4 Discussion

This work reported details of the implementation of the pSPM analysis approach to infants' pressure data, providing methodological considerations related to the pSPM data processing implementation as well as initial reflections associated with changes in plantar pressure from the onset of walking to confident walking.

4.3.4.1 Methodological considerations

The use of pSPM in infancy is important to provide clear and unbiased insights into foot development. Traditional software for pressure data processing rely on the assumption that analysis is carried out on pressure data presenting geometrical and/or pressure gradient patterns of adults' feet (Ellis et al., 2011). Although regional analysis is advantageous under certain circumstances (e.g. offloading the diabetic foot), its use can be debatable in the context of development, due to the ongoing anatomical and structural changes of the infants' feet. These changes prevent the foot from acting typically as a functional unit and therefore undermine the relevance of common ROI boundaries implemented in typically developed feet. Therefore, by selecting a methodology that divides the foot into ROIs according to adults' feet features, researchers imply that the infant foot is a typically functional unit, ignoring its anatomical and functional characteristics.

Another important methodological aspect of this study is the testing protocol and its effect on pressure data in infancy. Infants were able to walk freely and uninstructed as opposed to being restricted to a straight line, causing inconsistent directions of foot progression and contact patterns. Therefore, it was reasonable to anticipate the presence of a high intra and inter individual variability. This lead to the assumption of the presence of population-level asymmetry in gait and related pressure patterns, which supported the choice of analysing left and right feet separately.

The presence of intra and inter individual variability associated with the unrestrained testing protocol could also contribute to reduced registration quality. However, the rigid ICP algorithm, enhanced by PCA, yielded low RMSEs in both left and right feet, demonstrating high accuracy in the within-infant registration procedure. This can be due to the closer intra-individual correspondences in feet dimensions. The quality of the within-infant registration was also shown in figure 19 (A), where the optimal overlap of points suggests a satisfying performance of the ICP algorithm to the present data set. Performance of CPD algorithm was slightly less accurate considering the visual representation of the registration (Figure 19, B). This could be explained by the high inter-individual differences in foot dimensions and profile on the pressure platform. Nevertheless, RMSEs were under 0.4 mm for both within and between-infants registration, which, considering the mean foot length and width, indicates good fit of the sources to the template. Moreover, the low SD reported in both registration suggested that the ICP and CPD algorithms performed consistently on the point clouds, without high between registration variations. These results suggest that the proposed methodology provided an effective and solid framework for plantar pressure data processing in infancy, characterised also by a high pixel resolution. Despite the strengths of pSPM, it has to be highlighted that this approach aims to look for differences between plantar pressure images that are found in the foot anatomical correspondences, and for this reason, it was necessary to exclude steps that were made only with one small part of the foot (e.g., forefoot, heel). This ensures that steps are compared using similar anatomical correspondences across the plantar foot surface, but at the same time, it led to exclusion of steps that are characteristic of the sample considered, limiting the use of this approach in certain data set (e.g., infants with idiopathic toe walking).

4.3.4.2 Functional considerations

This study suggests that after 2.2 months of independent walking experience, pressure significantly increases in the central left forefoot during gait. This has also been previously identified between four and seven years, and authors argued about anatomical foot changes taking place (Phethean et al., 2014). In this work, anatomical foot development is unlikely to occur at a rate that would cause significant differences in pressure to happen, due to the short period between stages of foot loading (2.2 months). It would be reasonable to argue that the increasing body weight might be causing infants to apply higher loads onto the plantar surface during walking. However, it is possible to appreciate a minimal increase in weight between new and confident walking stages (+0.5 kg; ~ 5% of initial body weight), which correspond to the ~5% increase in foot length. A previous comparison of infants (mean age: 23.5 (5.7) months) identified statistically increasing pressure in the central forefoot between trials of walking and running (Hennig and Rosenbaum, 1991). The presence of dramatically increasing walking speed after few months of walking experience has also been documented (Hallemans et al., 2005; Hallemans et al., 2006). In case of this work, this could suggest that significant pressure changes in the central left forefoot could be attributed to the increasing walking speed, because of improvement in gait and acquisition of more confidence.

Significant increasing pressure in the central forefoot between these stages of foot loading has not been reported in the literature before, and it could be due to different methodological approaches adopted in this study compared to existing research. Bertsch et al. (2004) found that during the first year of independent walking, the whole forefoot demonstrated significantly increasing pressure. However, the exact anatomical location of such change was unknown due to the application of a whole forefoot region. This implies that differences in pressure distribution could have been anywhere within the boundaries of the forefoot, limiting considerations regarding plantar pressure changes in the transition to confident walking. Increasing the resolution of the forefoot mask (e.g. lateral, central, and medial forefoot) might lead to the detection of significant differences in the central forefoot. However, statistical outcomes would be highly dependent on the ROI selected (definition and number of ROIs), which likely causes arbitrary and inconsistent exploration of infants' pressure data.

Other changes in pressure were identified also qualitatively in both feet, and specifically in the central heel, medial to lateral forefoot and hallux (Figure 20 and 21). Previous works demonstrated that pressure in the hallux is the highest during the first few months of independent walking but decreases after three to six months of walking (Bertsch et al., 2004; Bosch et al., 2010; Hennig and Rosenbaum, 1991). The literature also report significant increasing heel pressure during the first year of independent walking (Bertsch et al., 2004), as initial heel contact occurs as opposed to forefoot contact (Hallemans et al., 2003; Hallemans et al., 2006). Findings from our work are in agreement with previous studies and suggest that changes in pressure occur rapidly, as infants become confident in walking. As opposed to previous works reporting data in infancy for either left feet, right feet, or mixed (Alvarez et al., 2008; Bertsch et al., 2004; Bosch et al., 2010), the present work showed different statistical results in left and right feet. This could be the related to the presence of high inter-limb asymmetry during the first months of walking (Ledebt et al., 2004), which lead to different pressure changes in the left and right feet between early and confident walking. However, because a large area of non-significant pressure increase is visible in the right foot (Figure 21), differences in statistical outcomes might be due to the small sample size analysed, in terms of both the number of participants and steps included in the analysis. Using a small sample might have caused the variability of the data to prevent significant differences being present in the right foot. This could also explain why larger areas of significant changes in pressure were not detected in both feet during the transition to confident walking, suggesting that confidence in these functional results has to be cautious and that further application of pSPM on a larger sample of infants is necessary to either confirm or reject the present results.

4.3.5 Limitations of the study

As anticipated in the discussion, the present section of this chapter is limited in relation to the sample size considered for the analysis. Combining pressure data from left and right feet by mirroring would have provided larger sample size, but this would have been in contrast with previous studies adopting pSPM, which reported data for both feet. Moreover, combining data of both feet would have also implied population-level symmetry in gait and related pressure patterns, which requires further investigation in the present sample. Finally, as mentioned at the end of section 4.3.4.1, this work did not considered steps that were made only with small parts of the feet (e.g., forefoot), thereby limiting the application of this data processing framework to steps that are also representative of the sample observed in this thesis, as well as other populations (e.g., idiopathic toe walkers).

4.3.6 Conclusion and thesis indications

Several phases of data processing were required to ensure robustness in the pSPM approach proposed in the present section. Despite this, the proposed methodology was showed being robust, accurate, high-resolution, and therefore appropriate for reporting and analysing infants' pressure data. Nevertheless, additional work should be undertaken to investigate whether differences in pressure are present between left and right feet, which would illuminate population-level symmetry in plantar pressure patterns. If left and right feet do not present differences in pressure, data between the feet could be combined, for example by mirroring one foot to the other, averaging pressure images between feet and thereby increasing the data sample per participant. Furthermore, future research analysing a larger sample with pSPM may have the capability to detect the presence of plantar pressure changes that have not been reported before providing a full account of changes in plantar pressures in the transition to confident walking. In addition, future works could also select factors associated with development such as increasing body weight, body height, and foot length to understand whether the overall body maturation could predict changes in pressures in infancy. Therefore, further investigations with the present methodology are warranted, to increase resolution of data analysis and ensure a clearer understanding of foot function development, as infants become confident in walking.

4.4 Summary and conclusions

This chapter aimed to investigate the appropriateness of different methodological approaches to reporting, analysing, and interpreting infants' plantar pressure data, informing the analytical methodology to be adopted within the thesis.

Despite the standard mask is the conventional approach to plantar pressure data in adults and in the paediatric sample, some factors were considered related to its use in infancy. Accordingly, the approach did not consider the unique developmental characteristics of the infant foot, with the risk of biasing pressure information by relying on foot regions generally defined upon typically developed feet. The customised mask proposed in this chapter identified ROIs using specific foot proportions of the sample analysed, and therefore was considered higher in resolution and more accurate in the definition of infants' foot regions than the standard masking approach, also mitigating pressure data loss. Thus, the strengths of the customised mask were represented by (i) the efficient batch processing of highly variable pressure data in shape, size, and spatial orientation and (ii) the simplicity of mask implementation. These characteristics makes its use appealing in both research and clinical practice, and application of this mask could be easily reproduced in a sample with the same foot measures.

Although easy to use and reproduce in other research, statistical data treatment with masking analysis is discrete, limiting the possibility to identify changes in the anatomical foot correspondence and treating ROIs as independent to each other. The proposed pSPM data processing framework was proven an accurate and robust alternative to infants' pressure data analysis, and its high-resolution makes it more suitable to compare statistically plantar pressure data across infancy. This would enhance not only a better understanding of foot function development but would also constitute an unbiased methodological approach to infants' pressure data analysis that could be used also in future works. Therefore, both the customised-automatic mask and the pSPM processing framework proposed in this chapter are suitable approaches to analysing infants' plantar pressure data. The following chapter will report plantar pressure data of pull to stand, onset of walking and confident walking using the customised mask (chapter 5), whilst statistical comparison between stages of walking will be carried out using pSPM (chapter 7).

Chapter 5. Describing plantar pressure patterns in the development of bipedal, independent locomotion

5.1 Introduction

As infants grow, the ability to move around independently, whether by crawling, pulling up to stand or walking represents an opportunity for infants to learn complex motor tasks and explore the surrounding social environment, interact, and engage with others (Adolph et al., 2016). The establishment of bipedal independent locomotion is an essential landmark for the overall development of infants, as it enhances changes to occur at various levels such as psychologically, emotionally, and physically (Kretch et al., 2014). Achievement of different motor milestones is also an important indicator of the overall development of the infant, and constitute the baseline for differentiation of more complex motor tasks and skills (Bushnell and Boudreau, 1993). Although establishment of walking is one of the major motor achievements in infancy, several motor milestones are performed before, where the foot plays important roles. For example, Between 8 to 15 weeks of age, it has been demonstrated that infants use their feet to reach for toys instead of using their hands (Galloway and Thelen, 2004). Moreover, the feet of new-borns are also used as a sensory organ, to provide information regarding the position of infants in space (Thelen, 1995).

Quantifying plantar pressures as infants learn and master different weight bearing motor tasks constitutes valuable information for clinical and research settings. Accordingly, it enhances knowledge of the typical plantar pressure patterns performed throughout periods of development, which could provide specific information related to foot function characteristics during the attainment of different weight bearing motor milestones. The importance of such investigations is also increased by capturing real-world plantar pressures in a nursery-style environment, allowing infants to move freely as they would during their every-day activities. During walking for example, Adolph et al. (2018) reported that starting and ending points are arbitrary and infants walk around in highly variable trajectories apart from straight lines. Hence, natural movement during walking can increase acquisition of real-world pressure data and reduce bias information related to typical foot function. Nevertheless, plantar pressure data prior to acquisition of walking skills has not been investigated in the literature. The events surrounding the development of the foot as a weight bearing structure are periods when key developmental stages occur, independent of the effect of bearing weight, or as a result of bearing non walking weight, such as those during crawling, shuffling, or pulling up to stand. Ignoring such events therefore limited the knowledge of the typical foot biomechanics prior to walking. Furthermore, the lack of a standardised protocol to capture and analyse infants' pressure data is an important limitation to consider in developmental studies, with specific challenges related to recruitment strategies, data collection and low-resolution approaches to plantar pressure data analyses. Therefore, this chapter aims to describe, for the first time, plantar pressure data in the transition from pull to stand to confident walking, using a high-resolution masking approach, which will help identify typical plantar pressure patterns at various stages of weight bearing motor development.

5.2 Research question

1. What are the typical plantar pressure patterns in trials of pull to stand, the onset of walking and confident walking?
2. What considerations can be highlighted from description of plantar pressures at each stages of motor development?

5.3 Methods

A full account of the materials, methods and ethical approval have been presented in chapter 3 and thus, the following sections will offer a synopsis of the participants analysed in the work and the testing procedure, with a specific focus on data processing and analysis.

5.3.1 Design

This chapter presents findings and interpretation of plantar pressure data of infants at different stages of motor development in a descriptive longitudinal design.

5.3.2 Participants

For this chapter, participants who attained all three visits namely pull to stand (V1), onset of walking (V2) and confident walking (V3) were included. Infants were recruited in the Northwest (University of Salford) and Southeast (University of Brighton) of England, through infants' facilities, local communities, and groups such as church groups. Infants were able to participate if they were born full-term, without impairment in attaining walking stages or gross motor development deficiency. Infants were excluded if diagnosed, had history of or were referred to consultation for neurological or musculoskeletal conditions.

5.3.3 Testing procedure

At each visit, parents were invited to the Universities for testing, and they had to attend each visit within 21 days since the attainment of the milestone, or they were excluded from the analysis. During each visit, plantar pressure data was collected using a Novel EMED xl platform (Novel, Munich, Germany), collecting at 100 Hz and with a sensor resolution of 4 sensors per cm^2. Videos were also recorded at each visit at both Universities (University of Brighton: Vicon Bonita 720c, Oxford, U.K/ University of Salford: Logitech HD Pro Webcam). The platform was placed in the middle of a nursery-style environment, and embedded in a soft mat, to ensure safety during testing (Figure 7). Overall, the testing protocol was undertaken in an unrestricted way, which means that infants were able to move in the space, as they preferred, without being constraints to perform the motor task in specific ways. In V1, infants were encouraged to pull up to stand onto a foam box by parents positioned on the opposite side of the foam box. In V2 and V3, infants were able to walk freely, to the extent of their abilities, at self-selected speed and in self-directed directions. The pressure system was triggered once infants initiated the motor task for 60 seconds. Detailed description of the three visits is reported in chapter 3.

5.3.4 Data processing

5.3.4.1 Pressure data extraction

Left and right steps were extracted as single files from the main trials of each participant at each visit, using the EMED software (Novel, EMED; Germany). For the three visits, steps were processed as maximum pressure pictures (MPPs) only if the entire foot was placed within the platform borders. Given the unrestricted testing protocol, videos of infants pulling up to stand and walking around the space ensured the categorisation of the MPPs according to the tasks performed by the infants at each visit. Specifically, both left and right pressure data of pull to stand were processed if they were computed from a stance phase that started and finish within the trial. Specifically, start phase of pull to stand movement was defined when a part of the foot (e.g. the heel, forefoot) made the first contact with the ground whilst infants were attempting to pull themselves up to stand against the foam box. The step was considered usable for the analysis if the foot remained in contact for the entire duration of pull to stand movement and then left the ground once infants were standing (Figure 22). The use of pressure data originating from a finished task was applied as criterion also to include steps in V2 and V3. In addition, infants at these stages performed many tasks apart from walking straight (e.g., they walked in curved paths, the squatted, walked sideways, stood still), which were excluded from the analysis to ensure capturing and interpreting data belonging to walking in straight lines only (chapter 3).

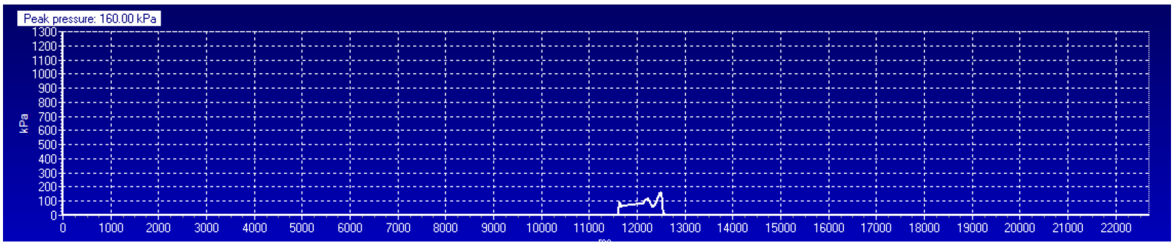
5.3.4.2 Masking analysis approach

Once both left and right MPPs of pull to stand and walking stages were extracted and labelled, a customised-automatic eight-region mask was created: medial heel, lateral heel, medial midfoot, lateral midfoot, medial forefoot, lateral forefoot, medial toes, lateral toes. Regions were defined based on percent foot length and width of the sample (Paley et al., 2000) (see chapter 4, section 4.2 for details). MPPs were grouped by visit, task, and feet (left or right), and the mask was applied to each MPP in the group using the Group Editor package. Next, the Groupmask Evaluation package was used to extract pressure data out of each masked MPP. A correct mask application was established to each MPP by visual inspection. If the mask did not apply correctly, that MPP was removed from the initial group, then a new group was created and mask evaluation was run again.

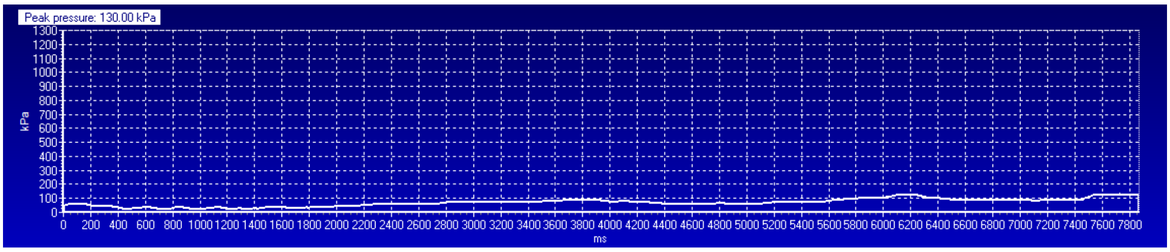
Data for each group was exported in text format and pressure was exported in Microsoft Excel as single values for each MPP of each participant, for five pressure variables, used as the mostly reported in infants' pressure studies. These were absolute contact area, relative contact area (% total foot), peak pressure, contact time, contact time as percent of roll over process (ROP) (Bertsch et al., 2004; Bosch et al., 2010; Hennig and Rosenbaum, 1991; Muller et al., 2012). The single values of the individual MPPs for each pressure variable were averaged in order to obtain one mean value per infant, per foot, for each of the three visits.

Figure 22. Example of stance phase of pressure data (Novel, EMED; Germany) which stance phase started and finished within the main trial (1) and stance phase that was captured from a foot that did not leave the ground before the end of the main trial (2).

(1)



(2)



5.3.5 Data analysis

Data was treated with Microsoft Excel (Windows 10) and analysis was carried out using the SPSS software (IBM Statistics, version 25). Chapter 4, section 4.3 highlighted the presence of different outcomes in statistical analysis between left and right feet. Therefore, pressure data of both left and right feet was imported into SPSS to check for differences between feet firstly. This was not part of the aims for this chapter, but it was considered as a general data management requirement that allowed describing characteristics of foot function in each milestone. Accordingly, the presence of differences in pressure between feet would enable to infer about feet asymmetry in function, whilst the absence of differences would allow combining data for both left and right feet and drawing conclusions of foot function using a higher data sample. As a result, data for the five different variables at each visit, for each region and foot was firstly checked for normality using the Shapiro-Wilk test (Ogunleye et al., 2018). Normality test revealed that data was not normally distributed. Therefore, statistical test to establish the presence of differences in pressure between left and right feet was undertaken using nonparametric inferences, namely Wilcoxon Signed Ranks test.

Once the presence of differences between feet was established for all the three visits, descriptive analysis of pressure data was undertaken by reporting median and quartiles in each milestone and region for all the pressure values used, to provide boundaries of normality in foot function across different developmental motor milestones

5.4 Results

In this chapter, 33 infants (14 females) were analysed with demographics reported in table 4.

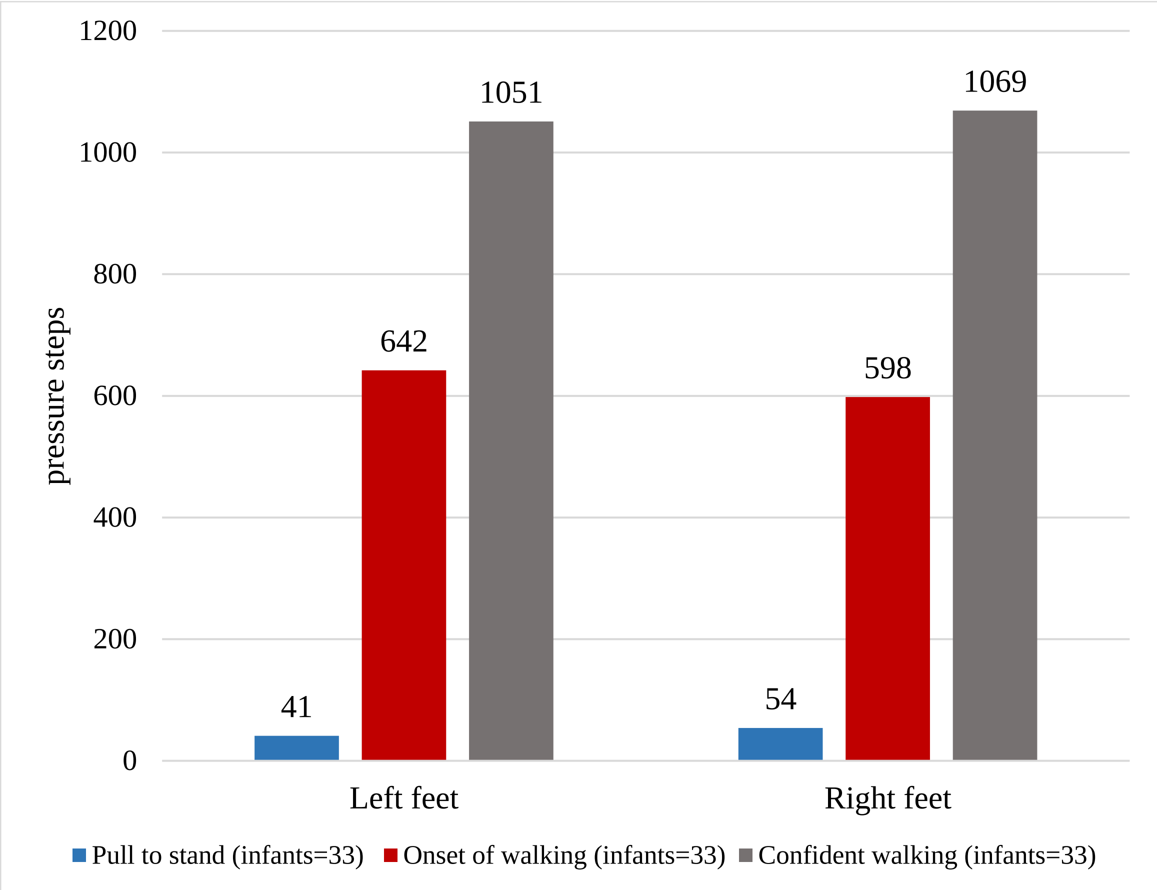
Table 4. Sample demographics of Chapter 5.

	Pull to stand (V1)				Onset of walking (V2)				Confident walking (V3)			
Measures	**Min**	**Mean**	**SD**	**Max**	**Min**	**Mean**	**SD**	**Max**	**Min**	**Mean**	**SD**	**Max**
Age at visit (months)	5.1	8.9	1.6	13.5	9.1	13.2	1.6	16.6	12.3	15.5	1.7	19.3
Age at milestone (months)	4.7	8.4	1.6	13.0	8.6	12.7	1.5	16.2	11.8	15.0	1.7	18.8
Days since milestone (days)	2.0	12.7	5.2	21.0	7.0	14.4	5.3	21.0	3.0	14.8	5.8	21.0
Mass (kg)	6.9	9.0	1.1	11.4	8.2	10.4	1.2	13.8	8.9	11.1	1.3	14.0
Height (cm)	63.5	70.4	3.3	75.6	68.5	74.9	3.0	81.8	71.9	78.7	3.7	85.0
Foot length (cm)	8.5	10.2	0.9	11.8	9.7	11.4	0.7	12.6	10.5	12.0	0.8	13.6
Foot width (cm)	4.0	4.8	0.5	6.4	4.4	5.2	0.4	6.0	4.0	5.2	0.5	6.2

5.4.1 Pressure data overview

During trials of pulling up to stand (V1) and walking (V2, V3), a different amount of data were collected with both left and right feet (Figure 23). In V1, right steps exceeded the left ones (n=41 VS n=54), as for V2 (n=642 VS n=598). In V3, the amount of data for the right foot was higher (n=1069) in comparison with the left one (n=1051).

Figure 23. Overall amount of left and right pull to stands (V1) and walking straight pressure data (V2, V3) in the three milestones.



The results obtained performing the Wilcoxon Signed Ranks tests revealed that in V1, significant differences between left and right feet were present only for contact area and peak pressure in the medial forefoot (Z= -2.135, p = 0.03) and the lateral forefoot (Z= -2.483, p=0.01), respectively. In V2, no significant differences were found for any of the pressure variables selected between left and right feet. In V3, significant differences between left and right feet were found for contact area in the lateral midfoot (Z=-2.049, p=0.04) and in the medial toes (Z=-2.385, p=0.01). With respect to peak pressure, left and right feet differed significantly in the lateral forefoot (Z= -2.117, p= 0.03).

Because significant differences were inconsistent and only in few regions of the pressure variables selected, data of left and right feet were averaged and reported hereafter. As a result, the amount of pressure data analysed in V1, V2 and V3 was 95, 1,240 and 2,120, respectively. In V1, the amount of data used per infant in V2 had a median of n=2, with a interquartile range (IQR) of 1. In V2 and V3, the number of pressure data for each infant had a median of 34 (IQR=17) and 62 (IQR= 26), respectively.

5.4.2. Descriptive analysis of pressure data

5.4.2.1 Pull to stand (V1)

Descriptive statistic (median, 25th and 75th quartiles) for pull to stand trials is reported in table 5.

Absolute and relative contact area

Values for absolute contact area demonstrated that the highest area in contact with the ground was found in the lateral midfoot and forefoot, with median values of 5.8 and 6.4 cm^2, respectively. On the other hand, the toes demonstrated the lowest values, with 3.8 and 3.3 cm^2 found in the medial and lateral, respectively. The absolute area covered by medial heel, lateral heel and medial forefoot was almost equal (5.1, 5.3 and 5.3 cm^2), whilst the medial midfoot recorded an absolute value of 4.8 cm^2. The highest variation in the data was observed in both forefoot regions as well as in the lateral midfoot, whilst dispersion of the data around the median for the other regions was small. With respect to the relative contact area, the surface of the foot was occupied mostly by the lateral regions compared to the medials. Specifically, the lateral forefoot covered 16.8% of the total area of the foot, followed by the lateral midfoot (15.1%), whilst the lateral toes occupied the smallest part (7.6%).

Peak Pressure

Overall, peak pressure values were the highest in the medial heel (85 kPa), followed by the lateral heel (82.5 kPa) and the medial toes (70 kPa). Among the medial and lateral midfoot and forefoot regions, values ranged between 53.8 kPa and 57.5 kPa, whilst the lowest value was found in the lateral toes (40 kPa). Inter-individual variation in the forefoot regions was the highest.

Absolute and relative contact times

With respect to absolute contact time, the data shows an almost equal distribution across the 8 regions, with median ranging between 4700 and 5940 ms. In this case, the medial toes expressed the lowest value (4700ms), whilst the highest time in contact with the ground was spent by the lateral midfoot (5790 ms) and lateral forefoot (5940 ms). The data also demonstrated a high degree of variations across all the regions, but mostly in the forefoot regions. With respect to relative contact times (expressed as percent of the stance), 93.7% of the full pull to stand cycle was occupied by the lateral forefoot, followed by the medial forefoot (92.9%) and the lateral midfoot (84.0%). As opposed, the lateral toes occupied the lowest part of the pull to stand cycle (70.1%). Data variation was high in all the regions except for the midfoot regions, where the quartiles were closer to the median.

Table 5. Descriptive statistics of absolute (cm^2) and relative contact area (% total foot), peak pressure (kPa), contact time (ms), contact time (% rollover process) of infants at V1.

Pull to stand (V1)									
Contact area (cm^2)									
		Medial heel	**Lateral heel**	**Medial midfoot**	**Lateral midfoot**	**Medial forefoot**	**Lateral forefoot**	**Medial toes**	**Lateral toes**
Median		5.10	5.30	4.30	5.80	5.30	6.40	3.80	3.30
Quartiles	**25**	4.30	4.40	3.45	4.60	4.10	5.55	3.10	2.40
	75	6.10	6.45	5.00	6.75	6.45	7.75	4.90	4.00
Relative contact area (% total foot)									
		Medial heel	**Lateral heel**	**Medial midfoot**	**Lateral midfoot**	**Medial forefoot**	**Lateral forefoot**	**Medial toes**	**Lateral toes**
Median		13.3	13.6	10.6	15.1	13.2	16.8	9.0	7.6
Quartiles	**25**	10.8	11.7	9.4	11.8	11.1	13.9	7.9	6.1
	75	15.3	15.8	12.3	15.9	16.2	18.8	11.9	11.1
Peak Pressure (kPa)									
		Medial heel	**Lateral heel**	**Medial midfoot**	**Lateral midfoot**	**Medial forefoot**	**Lateral forefoot**	**Medial toes**	**Lateral toes**
Median		85.0	82.5	53.8	55.0	57.5	55.0	70.0	40.0
Quartiles	**25**	70.3	69.6	41.3	42.4	44.4	44.4	51.9	29.0
	75	104.9	102.5	60.0	70.0	87.5	83.2	86.8	58.0
Contact time (ms)									
		Medial heel	**Lateral heel**	**Medial midfoot**	**Lateral midfoot**	**Medial forefoot**	**Lateral forefoot**	**Medial toes**	**Lateral toes**
Median		5260.0	4770.0	4775.0	5790.0	5340.0	5940.0	4700.0	5108.0
Quartiles	**25**	2197.5	2259.0	2584.1	2565.2	3022.5	2927.5	2188.4	2755.0
	75	9345.0	8730.0	9917.5	9860.0	11065.0	10358.8	10002.5	9812.5
Contact time (% ROP)									
		Medial heel	**Lateral heel**	**Medial midfoot**	**Lateral midfoot**	**Medial forefoot**	**Lateral forefoot**	**Medial toes**	**Lateral toes**
Median		76.2	78.9	81.9	84.0	92.9	93.7	82.1	70.1
Quartiles	**25**	61.5	61.0	66.4	77.1	84.6	77.9	65.1	58.5
	75	88.5	88.6	90.4	91.6	98.3	97.2	93.6	89.7

5.4.2.2 Onset of walking (V2)

Descriptive statistics (median, 25^{th} and 75^{th} quartiles) of the onset of walking trials are reported in table 6.

Absolute and relative contact area

Absolute values for contact area revealed that the lateral midfoot and the forefoot regions demonstrated the highest contact area at the onset of walking, with values reaching 7.5, 7.3 and 7.9 cm^2, respectively. The area covered by the medial heel (6.3 cm^2), lateral heel (5.9 cm^2) and medial midfoot (5.9 cm^2) was almost equal, whilst the regions with the lower value were the medial toes (4.5 cm^2) and lateral (1.8 cm^2). Data variation was low in all the regions, but the highest spread was found in the medial midfoot. With respect to the relative contact areas, infants at the onset of walking showed that the lateral and medial forefoot covered 15.9 and 16.7% of the total area of the foot, followed by the medial and lateral midfoot (12.9% and 15.8%) and the medial and lateral heel (13.3% and 12.7%). The toes still occupied the smallest area of the foot, with the medial and lateral toes covering 9.6% and 3.8% of the total area of the foot, respectively.

Peak pressure

The medial heel was the region with the highest peak pressure (103.3 kPa), followed by the medial toes (99.6 kPa) and the lateral heel (98.7 kPa). The lowest value was found in the lateral toes, with 14.9 kPa. The most variable region was the medial forefoot and medial toes, although also the heel regions were subject to variations within their data.

Absolute and relative contact times

Absolute contact time was the highest in the medial forefoot (787.9 ms), followed by the medial toes (763.8 ms) and the lateral forefoot (754.3 ms). The values were lower in the medial heel (570 ms), lateral midfoot (651.6 ms) and medial midfoot (623.5 ms). Again, the lowest contact time was detected in the lateral toes. Differently from contact area and peak pressure, in this case variation of the data was abundant in all the regions, but especially within the forefoot regions. With respect to relative contact time, values are in accordance with absolute contact time and suggests that the medial forefoot was in contact with the ground for 90.6% of the total stance phase, followed by the lateral forefoot (87.8%). The midfoot regions occupied an almost equal amount of stance phase (76.6% and 76.9%, respectively), as the heel regions (69.4% and 68.2%, respectively). This is different for the toes regions, where the lateral toes occupied only 22.2% of the stance, whilst the medial heel reached 74.3%. Data was highly variable in the medial toes and lateral toes, where the spread of the data was mostly present in the upper quartile.

Table 6. Descriptive statistics of absolute (cm2) and relative contact area (% total foot), peak pressure (kPa), contact time (ms), contact time (% rollover process) in infants at V2.

Onset of walking (V2)									
Contact area (cm²)									
		Medial heel	**Lateral heel**	**Medial midfoot**	**Lateral midfoot**	**Medial forefoot**	**Lateral forefoot**	**Medial toes**	**Lateral toes**
Median		6.3	5.9	5.9	7.5	7.3	7.9	4.5	1.8
Quartiles	**25**	5.7	5.5	5.1	6.9	7.0	7.4	4.1	1.6
	75	6.7	6.3	6.5	7.6	7.9	8.4	4.7	2.1
Relative contact area (% total foot)									
		Medial heel	**Lateral heel**	**Medial midfoot**	**Lateral midfoot**	**Medial forefoot**	**Lateral forefoot**	**Medial toes**	**Lateral toes**
Median		13.3	12.7	12.9	15.8	15.9	16.7	9.5	3.8
Quartiles	**25**	12.0	12.0	11.0	14.8	15.4	16.0	9.2	3.3
	75	14.2	13.2	13.6	16.5	16.7	17.6	9.9	4.3
Peak Pressure (kPa)									
		Medial heel	**Lateral heel**	**Medial midfoot**	**Lateral midfoot**	**Medial forefoot**	**Lateral forefoot**	**Medial toes**	**Lateral toes**
Median		103.3	98.7	71.5	72.4	77.0	53.8	99.6	35.0
Quartiles	**25**	95.6	92.6	64.7	69.5	65.1	46.5	90.5	26.8
	75	115.5	112.3	77.5	78.6	93.0	63.0	117.9	43.0
Contact time (ms)									
		Medial heel	**Lateral heel**	**Medial midfoot**	**Lateral midfoot**	**Medial forefoot**	**Lateral forefoot**	**Medial toes**	**Lateral toes**
Median		570.2	620.8	623.5	651.6	787.9	754.3	763.8	554.3
Quartiles	**25**	487.4	495.5	529.8	538.0	614.1	619.7	540.7	442.5
	75	800.0	784.9	916.3	940.9	1113.9	1149.7	981.3	790.2
Contact time (% ROP)									
		Medial heel	**Lateral heel**	**Medial midfoot**	**Lateral midfoot**	**Medial forefoot**	**Lateral forefoot**	**Medial toes**	**Lateral toes**
Median		69.4	68.2	76.6	76.9	90.6	87.8	74.3	58.0
Quartiles	**25**	62.6	61.6	71.2	73.9	88.2	84.4	65.7	49.2
	75	73.0	71.9	79.3	80.1	92.9	90.3	80.7	72.9

5.4.2.3 Confident walking (V3)

Table 7 reports descriptive data of infants confidently walking.

Absolute and relative contact area

During this period, absolute contact area values were the highest in the lateral forefoot (8.2 cm^2) and medial forefoot (7.9 cm^2). The area covered by the lateral midfoot was greater than the medial, with values reaching 7.7 and 5.5 cm^2, respectively. Absolute contact area values of the heel regions was almost the same (6.3 and 6.4 cm^2), whilst the contact area of the medial toes (4.9 cm^2) was greater than twice the area of the lateral toes (1.9 cm^2). Both quartiles demonstrate also a minimal spread of data around the median. Similarly, the forefoot regions were the areas covering more surface of the total foot in comparison with other regions (17.0 and 16.1% for medial and lateral forefoot, respectively), with small variations around the medians. Again, the toe regions occupied the smallest area relative to the total foot (9.4 and 4.1% for medial and lateral toes, respectively).

Peak pressure

With respect to peak pressure, the heel regions recorded the highest values, with medial and lateral heel demonstrating 108.7 and 104.8 kPa, respectively. These decreased in both the midfoot regions, where the medial region demonstrated lower values (70.9 kPa) in comparison with the lateral regions (73.9 kPa). Pressure in the forefoot reduced in the lateral to 59.2 kPa, whilst it increased in the medial (82.2 kPa) region. This pattern remained in the toe regions, where higher pressure was present is the medial (96.8 kPa) compared to the lateral (33.5 kPa) toes. As for absolute contact area, in general both quartiles suggested a low spread of the data around the median, except for the medial toes, where the largest variation was present in the upper quartile.

Absolute and relative contact times

As infants were walking confidently, absolute contact time values were more variable, especially within the forefoot regions and the medial toes. Specifically, the medial and lateral forefoot were the regions with the highest contact times (669.5 and 664.1 ms), followed by the midfoot regions, where values in the lateral midfoot (577.4 ms) exceeded those in the medial (533.2 ms). In the heel regions, contact times were similar between the medial heel (503.2 ms) and lateral heel (507.8 ms). This was different from the toe regions, where contact time was higher in the medial toes (598 ms) than the lateral (457.8 ms). Contrasting from the absolute values, data of relative show small amount of data variations, apart from the toe regions, where the highest spread of the data around the median was present. Between the concomitant lateral and medial regions, the percent of time spent in relation to the stance phase was almost equal. For example, the medial and lateral heel occupied 68.3 and 68.8% of the stance phase, and similarly the medial and lateral midfoot (75.1 and 76.6%). This was different within the forefoot regions, where the relative contact time was higher in medial forefoot (89.3%) compared to the lateral (85.9%). However, within the forefoot regions, the relative contact times in the medial and lateral toes were different, with 71 and 51.8% respectively.

Table 7. Descriptive statistics of absolute (cm^2) and relative contact area (% total foot), peak pressure (kPa), contact time (ms), contact time (% rollover process) in infants at V3.

Confident walking (V3)									
Contact area (cm^2)									
		Medial heel	**Lateral heel**	**Medial midfoot**	**Lateral midfoot**	**Medial forefoot**	**Lateral forefoot**	**Medial toes**	**Lateral toes**
Median		6.3	6.4	5.5	7.7	7.9	8.2	4.6	1.9
Quartiles	**25**	5.8	5.7	5.0	7.1	7.1	7.9	4.0	1.6
	75	6.9	6.7	6.5	8.1	8.2	8.6	4.9	2.1
Relative contact area (% total foot)									
		Medial heel	**Lateral heel**	**Medial midfoot**	**Lateral midfoot**	**Medial forefoot**	**Lateral forefoot**	**Medial toes**	**Lateral toes**
Median		13.0	12.8	12.2	15.8	16.1	17.1	9.4	4.1
Quartiles	**25**	12.1	12.1	11.1	15.1	15.7	16.0	8.9	3.3
	75	14.2	13.7	13.1	16.5	16.6	17.5	9.8	4.3
Peak Pressure (kPa)									
		Medial heel	**Lateral heel**	**Medial midfoot**	**Lateral midfoot**	**Medial forefoot**	**Lateral forefoot**	**Medial toes**	**Lateral toes**
Median		108.7	104.8	70.9	73.9	82.2	59.2	96.8	33.5
Quartiles	**25**	99.7	97.2	65.2	68.8	72.8	53.2	84.4	24.9
	75	116.9	113.1	78.1	78.2	92.6	66.9	114.8	42.9
Contact time (ms)									
		Medial heel	**Lateral heel**	**Medial midfoot**	**Lateral midfoot**	**Medial forefoot**	**Lateral forefoot**	**Medial toes**	**Lateral toes**
Median		503.2	507.8	533.2	577.4	669.5	664.1	598.0	457.8
Quartiles	**25**	453.0	451.9	486.8	495.6	569.9	555.2	435.4	367.8
	75	669.5	707.3	774.2	788.6	938.4	940.6	851.0	605.6
Contact time (% ROP)									
		Medial heel	**Lateral heel**	**Medial midfoot**	**Lateral midfoot**	**Medial forefoot**	**Lateral forefoot**	**Medial toes**	**Lateral toes**
Median		68.3	68.8	75.1	76.6	89.3	85.9	71.0	51.8
Quartiles	**25**	64.3	64.0	71.8	74.1	87.3	83.1	62.0	45.4
	75	72.5	71.2	78.2	79.9	91.1	89.5	79.0	64.3

5.5 Discussion

This chapter aimed to describe, for the first time, typical plantar pressure patterns in the transition from pull to stand to confident walking, using a high-resolution masking approach, which has the potential to highlight novel aspects of plantar pressure across infancy.

5.5.1 Plantar pressure patterns across milestones

5.5.1.1 Pull to stand (V1)

Pulling up to standing is an infant's first attempt to initiate independent bipedal locomotion (Adolph and Franchak, 2017), and it can be considered as one of the major motor achievements in infancy. When infants start to pull to stand, they achieve a new position to explore, interact with others and play (Alexander et al., 1993, Bly and Ariz, 1995), which improves proprioceptive and visual information (Metcalfe et al., 2005, Chen et al., 2007). As a result, pull to stand has been described as an important transitional period of development that leads to establishment of subsequent developmental stages such as walking (Piek et al., 2008). Despite the significance of this milestone, it remains largely unexplored from a biomechanical perspective. The role of the foot during this task and the loading it experiences has not previously been described and the functional characteristics of the foot in this early upright bipedal motor task are yet to be explored. As a result, little is understood about the role of the feet during pull to stand.

The results demonstrated that trials of pull to stand were performed using mainly the right foot (Figure 23). This might suggest that the right foot was more active during trials of pull to stand, and shows a preference of foot choice in the performance of the motor task. Findings from a previous observation make reasonable to surmise that the use of foot might be influenced by the different motor strategies infants can adopt to adopted to pull themselves up to stand (Atun-Einy et al., 2012). Accordingly, Atun-Einy et al. (2012) demonstrated that infants initially use two legs as a simultaneous unit when performing trials of pull to stand, with the legs symmetrically extended behind and the arms supporting most of the weight (which it will be referred to as strategy A in this chapter). In case of strategy A, the amount of pressure applied onto both feet might likely be similar, as they would be loaded to pull up to stand following the same motor pattern. With increasing balance, coordination and soft tissues enforcement, infants start to adopt the half-knee strategy to pull up to stand (Atun-Einy et al., 2012). Accordingly, the centre of mass is shifted laterally and upwards (McMillan and Scholz, 2000, Harbourne and Stergiou, 2003), and a supporting leg is used independently to the other (Bly and Ariz, 1995) (which it will be referred to as strategy B in this work). In their work, Atun-Einy et al. (2012) followed 27 infants from seven months of age until they were 12 months (min age six and max age 14 months), in order to capture data from the onset of pull to stand development, offering an insightful view into the early establishment of bipedal locomotion. In this chapter, infants pulling up to stand had a mean age of nine months when they achieved the milestone (min age 5.1 and max age 13.5 months), and thus, they were younger on average in comparison with the sample of Atun-Einy et al. (2012). As a result, the present chapter might have missed some information related to development of improved pull-to-stand movement abilities. Inter-individual characteristics of pull to stand strategies have not been established, and thus, it is unclear whether the infants analysed performed pull to stand adopting strategy A or B, or mixed. However, knowledge of different stages of pull to stand development can inform interpretation of the present data.

Accordingly, it is reasonable to surmise that the higher amount of right pull to stand trials could be due to performance of half-knee strategy to pull to stand, with the right foot used as additional supporting surface alongside the knee and the hands. The presence of half-knee strategy in pulling up to stand could also explain the overall high variability in the pressure variables analysed. This strategy introduces more motor complexity into pull to stand, hence an increase in variability that is reflected at plantar level as infants learn how to perform the new upright locomotion strategy (Piek, 2002). High inter-individual data variability was demonstrated mainly in contact time values across the regions. Specifically, the median absolute contact time is similarly high among the regions, with values ranging between 4700-5790 ms across regions. Accordingly, normalised contact time values also show a similar trend, suggesting that all the regions spent a high amount of stance in contact with the ground. Thus, these findings suggested that in order to stabilise and sustain the body in bipedal position, infants required a prolonged contact with the ground before lifting the foot. This could be due to the time needed to integrate leg, trunk and arms movements and maintain balance as they attempt to stand upright efficiently.

The spread of contact time data around the median in each region denoted also high inter-individual differences. It is recognised that within this stage, infants were not differentiated based on their ability to pull up to stand. Hence some infants could have been able to cruise along the support straight after pulling up to stand, or simply felt confident in changing the type of support to a more stable position, thereby lifting the foot quickly and reducing the amount of time spent in contact with the ground from the moment they started to pull to stand. This could be supported by the inter-individual variation of days that passed (SD= 5.2 days, min=2, max=21) since parents reported the establishment of milestone achievement. Therefore, variations in contact time values could indicate that demands associated with performance of pull to stand tasks was different between infants at this stage.

Despite these considerations, results of this work highlighted that involvement of the forefoot during stance was high in infants pulling up to stand. This was supported by the largest amount of stance phase occupied by medial and lateral forefoot contact, with lateral forefoot showing also the highest absolute contact times. The persistent use of the forefoot during V1 might also be explained by considering how infants attempted to pull to stand. Accordingly, infants leant forward towards the supporting surface to achieve the bipedal position (Figure 8). By doing so, the load is applied anteriorly within the feet at initial contact, enabling infants to reach higher and towards the supporting surface efficiently. For example, if infants loaded the heel regions, it is likely that their lack of balance and control would lead them to fall on their back, as they would not have the neuromuscular ability to control backwards oscillations of their centre of mass. Furthermore, it is interesting to notice that the contact area of the medial forefoot and lateral forefoot combined is also the highest among the foot regions analysed in this work. The largest surface occupied by the forefoot would enable infants to increase balance and control as they pull to stand, thereby reducing falls and excessive perturbations in stability. Thus, using the forefoot regions as primary interface during pull to stand enabled infants to maximise their motor performance, resulting in the most efficient solution to enhance bipedal locomotion (Galna and Sparrow, 2006). Nevertheless, these considerations might benefit from future studies exploring pull to stand through combined biomechanical analyses (e.g. kinematic, electromyography) with plantar pressure data, which could clarify the dynamics of the whole body as infants load the foot to pull to stand.

As opposed to the medial and lateral forefoot, the region with the smallest absolute and relative contact area was the lateral toes, where also most of the other pressure variables (e.g. peak pressure, relative contact time) showed the lowest data. This could possibly be associated with the low surface occupied by the lateral toes, hence its minimal contribution in supporting and stabilising the infants as they perform the motor task. This is the opposite for the medial toes, for example, where one of the highest peak pressure is present among the foot regions (70 kPa). Despite the surface area in the medial toes was lower in comparison with heel, midfoot and forefoot regions, high peak pressure associated with high contact time values indicates that infants might take advantage of the typical adducted position of the hallux to increase their base of support.

The greatest peak pressures were however present in the medial and lateral heel, despite the contact time values with respect to stance were the lowest. If the forefoot was assumed being the first regions to make contact with the ground, then pressure at the heel would reasonably be applied after as infant attempt to pull to stand. The highest pressure in the medial and lateral heel might be caused by lack of a controlled foot placement to the ground. This could be due to the poor stability, as well as low foot and lower limb muscle strength and control at this stage of development, which causes the medial and lateral heel to drop down quicker as they load shifts from forefoot to heel regions during pull to stand. Accordingly, the heel hitting the floor with a high velocity would require a high deceleration to stop the heel, (as $F = m*a$), hence a high force would be recorded, leading to high-pressure values.

5.5.1.2 Onset of walking (V2)

In general, pressure data capture at the onset of walking displayed high variation between infants, specifically of peak pressure and contact time values for all the regions analysed. This could be due to different walking strategies adopted to progress forward. Specifically, McCollum et al. (1995) reported that three types of strategies to independent walking (twisters, fallers, and steppers) to facilitate forward progression and mitigate the postural constraints related with the lack of balance, coordination, and immature neuromuscular-skeletal system at this stage of development.

Nevertheless, peak pressure data showed that the medial regions of the foot (apart from the medial midfoot) were subject to higher pressure than the laterals. Accordingly, all the medial regions of the feet also occupied larger amount of stance in comparison with the laterals, suggesting a persistent and prolonged medial loading distribution at the onset of walking. The reason behind this pattern could be varied, but it is interesting to notice that Samson et al. (2011) demonstrated the presence of a greater ankle eversion moment in two years old infants. Ankle posture combined with the typical laxity of the infant foot could be causing the increasing medial foot loading. As opposed to previous studies however, the highest peak pressure was found in the medial heel rather than the hallux (medial toes), which was previously identified as the most loaded region up to eight months from the onset of independent walking (Hallemans et al., 2003, Bertsch et al., 2004).

Inconsistencies between findings might be due to the different approaches adopted to plantar pressure analyses. Accordingly, the above studies considered the heel region as a whole, without splitting it in its medial and lateral components. As a result, peaks in the data might have been mitigated by averages. For example, if the peak pressures of the medial and lateral heel were averaged in this work, a mean value of 101 kPa would be identified, which is similar to the peak pressure value found in the medial toes (99.6 kPa). Furthermore, the pressure within the hallux is lower than the range provided by existing research, which show that during the first eight months of independent walking, pressure in the hallux has been reported in a range of 120 and 180 kPa (Bertsch et al., 2004, Muller et al., 2012a, Hennig and Rosenbaum, 1991). Differences in peak pressures in the hallux between this work and existing research can be accounted for by considering several factors such as the amount of pressure data analysed, the demographics of the infants and the testing protocol adopted.

For example, the studies cited above analysed between three to five pressure steps per participant. On the contrary, this work used a minimum of nine steps per participants, with a maximum number of 91 in the combination of left and right feet, providing valuable and insightful information in relation to inter-individual characteristics of plantar pressures. Furthermore, the body weight in infants analysed by Hennig and Rosenbaum (1991) was 12.8 kg, more than 1 kg higher in comparison with the present sample's body weight, which might have caused different loading demands on the foot during walking. Finally, Muller et al. (2012) instructed infants to walk in straight lines as opposed to free walking. Given a fixed trajectory to follow with a reword or an object of desire to enhance straight line walking, it is reasonable to assume that infants might walk faster, hence greater amount of pressure being applied throughout the foot during stance.

Differently from the hallux and the heel, the medial midfoot showed lower absolute and relative contact areas, peak pressure, and absolute contact time values than its lateral counterpart. With this data, considerations can be made related to the function of the medial midfoot at the onset of walking. In fact, the foot is characterised by a low medial arch profile at this stage of development (Bertsch et al., 2004). This coupled with the great ankle eversion moment at the onset of walking (Samson et al., 2011) would make reasonable to expect high-pressure values in the medial midfoot. Nevertheless, these data suggest that foot shape and ankle posture does not seem to influence plantar pressures in the medial midfoot at the onset of walking.

With respect to forefoot regions, both lateral and medial regions demonstrated the highest absolute and relative contact time values, suggesting a prevalence of forefoot regions involvement throughout stance. Such involvement was however characterised by high inter-individual differences, demonstrated by high quartiles ranges of both variables. As a result, it is likely that at this stage of motor development, infants started to explore diverse ways to progress forward, thereby using the forefoot differently and for a different amount of time while accomplishing a step.

5.5.1.3 Confident walking (V3)

Overall, plantar pressure patterns of all the variables considered in infants confidently walking displayed a reduced inter-individual data variation around the median compared to infants at the onset of walking, suggesting a more consistent pressure application and foot contact pattern among infants during walking.

Data of the present chapter highlighted that confident walkers infants showed higher peak pressure and lower contact time values (both absolute and normalised to stance) in the medial and lateral heel compared to the other regions. This demonstrated an increasing activity of the heel during walking, which can be supported by findings of previous works. Accordingly, it has been reported that the initial contact with the heel starts being a predominant pattern as walking experience increases (Burnett and Johnson, 1971, Bertsch et al., 2004, Hallemans et al., 2003). In this work, considerations about initial heel contact are limited as regional pressure lack considerations with respect to the spatial domain of the data. In other words, it does not account for changes in pressure applications with respect to the start and end of the whole stance, which could be explored through analysis of foot kinematics or centre of pressure data.

Similar to infants who just started walk independently, the medial regions of the foot were subjects to higher pressure in comparisons with the lateral regions. As for V2 however, the only exception was made by the midfoot regions. Accordingly, all the pressure variables demonstrated lower values in the medial midfoot compared to the lateral, with values in the lateral midfoot exceeding those in the medial. Given the short time occurring between V2 and V3, it is unreasonable to assume that structural changes within the medial midfoot occurred. Despite the presence of an immature medial-arched foot, infants express medial midfoot function that resembles the one of typically arched feet, as it has been also reported in V2. As opposed to the midfoot, all the other regions showed higher loading applied in the medial counterparts. This is particularly evident when looking at pressure values of medial and lateral forefoot, for example. Overall, these regions were loaded for longer, and they occupied the largest amount of stance phase and contact area during walking. Although contact area values were similar between the lateral and medial forefoot (8.2 and 7.9 cm^2, respectively), higher peak pressure and contact time (absolute and normalised to stance) were present in the medial forefoot compared to the lateral.

This pattern of high medial loading might be due to the improved gait occurring in combination to the presence of an immature foot structure and lower limb posture. Accordingly, infants at this stage of development are likely to demonstrate more confidence in walking as they practice walking for more time. This might suggest the presence of quicker foot contacts, originating from the overall increasing walking experience, which is consistent with the lower contact time values in comparison with V2. As an example, Hallemans et al., (2006b) demonstrated that after five months of independent gait, walking speed increases in association with an increasing cadence. Spatial-temporal parameters of gait were not measured in this chapter. However, the highest number of steps taken in this developmental stage (Figure 23) suggests agreement with the work reported above. Nevertheless, it is also important to consider that confident walking infants were still characterised by an immature foot structure, as musculoskeletal maturation of the foot from the onset of walking would not occur in a way to enhance an increasing lateral pressure distribution. Furthermore, confident walking infants still have to face challenges related to maintaining postural balance as they walk, integrating control of muscle activity and limb coordination in each step. Previous studies have showed that, in the context of motor learning, movements that require less energy or effort to perform a specific task are preferred as optimal motor solutions (Galna and Sparrow, 2006, Sparrow et al., 2000). Therefore, it could be reasonable to assume that the increasing use of the medial sides of the foot might be the preferred path, or strategy, to enhance an efficient forward progression during confident walking.

5.5.2 General considerations

Overall, the above discussions enabled important considerations to be made related to the typical plantar pressures described in infants at pull to stand, onset of walking and confident walking. Specifically, by scoping plantar pressures in each of the stages of motor development, this work identified the presence of common patterns that perpetuates from pull to stand to confident walking.

For example, it is interesting to notice that during trials of pull to stand, the medial and lateral forefoot were the regions predominantly used to pull to stand. Similarly, the forefoot regions were highly involved in both V2 and V3. Therefore, it would be possible to argue that the forefoot could be considered an important structure to supporting infants in the accomplishment of bipedal, independent locomotion, which might be due to its larger surface in contact with the ground compared to the other regions of the foot (e.g. heel, hallux).

Another important common aspect within the three milestone is related to the higher peak pressures within the medial and lateral heel compared to the other regions analysed in each stage. The reasons behind highest medial and lateral heel pressure were different within the three visits, as the foot was used to accomplish different tasks in different conditions of stability and motor control, as highlighted in the previous sections. However, it is possible to assume that the function related to the heel regions was to bear greater loads, using this area as a converging pivot from where pressure is then applied to the other regions in the attainment of pull to stand and walking.

The medial midfoot represented the only exception to the increasing loading observed, as across all three visits, it did not show higher pressure than its lateral counterpart did. Furthermore, greater differences in pressure values between medial and lateral midfoot became more evident across all the three motor stages. As previously highlighted, this could be due to the early medial midfoot development, which demonstrate to function already as a typically developed unit, despite its structural immaturity (the low medial arch presence). A motor event associated with the possible presence of such medial midfoot characteristic is observable in all three visit. Accordingly, the foot has been showed to accomplish either a stable bipedal posture (V1) or forward progression (V2, V3). In both cases, it was possible to detect a pattern of pressure distribution from one part of the foot to another in all three visits. Therefore, the function of the typically arched medial midfoot to enhance pressure distribution across the plantar surface might be already present from pull to stand to confident walking stages, highlighting the presence of early functional patterns within the medial midfoot.

As a result, it would be reasonable to argue that the infant weight bearing foot demonstrated similarities in the use of different anatomical areas to accomplish independent bipedal locomotion. This could suggest that the typical plantar pressures identified at the onset of walking and confident walking might find their origin in preliminary stages of motor development, such as during trials of pull to stand, and increasingly change towards the typical patterns that have been studied up to date during stages of walking. This statement is however optimistic, as infants likely performed a series of different motor milestones between pull to stand and the onset of walking, such as cruising and walking supported (Adolph and Franchak, 2017) that were not analysed in this chapter. Therefore, the presence of perpetuating plantar pressure characteristics cannot be completely validated in this work. Nevertheless, this is the first time that such considerations have been made and could warrant further investigation to understand whether typical pressure patterns in stages of walking could be linked to the early use of the foot as infants learn and master the ability to pull themselves up to stand.

5.6 Limitation of the work

A higher amount of data has been obtained by analysing left and right feet together as opposed to separate the analysis. It is recognised that the absence of statistical differences between left and right feet within each milestone might not be enough to exclude differences in foot function among feet. Nevertheless, separating the analysis between left and right feet would have been useful if consecutive steps were analysed in the performance of each motor task, to detect functional behaviour of the two feet in relation to each other, which was not the aim of this work.

In this work, it has been highlighted that stages of pull to stand development exists, which can influence pressure patterns hence the role of the foot within this milestone. This is similar to the onset of walking, where infants adopt different strategies to enhance independent forward progression, which were not identified in this chapter and could influence plantar pressure patterns. Recognising the presence of characteristic motor patterns within each milestone and differentiate description of plantar pressure according to them could have enhanced knowledge of typical foot function in each stage without generalising.

Lastly, this chapter offered interpretation of data generated from pressure platform only, which could have benefited from associated kinematic or electromyography (EMG) data analysis. In fact, foot function is closely related to the lower limb and foot posture changes during gait, for example, as well as muscles activity maturation. Therefore, incorporating data from lower limb, foot kinematic, and EMG with plantar pressure could provide insights that are more detailed and a comprehensive knowledge regarding the function of the foot within stages of motor development.

5.7 Summary and conclusions

Overall, the above findings suggested that the dynamic requirements of each milestone, such as attaining bipedal posture (V1) and progressing forward (V2, V3), helped inform the specific plantar pressure changes in these stages. Differences with findings provided by previous work has however been demonstrated. For example, peak pressure in the hallux of infants at the onset of walking was higher in this work compared to existing literature. As a consequence, it has been highlighted the lack of consistent data reporting across studies, which is possibly due to differences in sample demographics as well as due to the variety of testing protocol and methodological approaches for pressure data treatment adopted in infancy. Accordingly, the present work captured data from tasks performed in habitual and friendly nursery-style environments, but at the same time undertaking a robust protocol for sample recruitment and data capture. Therefore, it has been able to characterise plantar pressures that represent every-day patterns, ensuring interpretation of real-world data.

Despite these remarks, findings from this work highlighted the presence of important and novel plantar pressure patterns that are specific to the individual developmental stages considered in this chapter, as infants motor abilities changed progressively, with foot loading demands modifying accordingly. In addition, description of plantar pressures in the three distinct stages enabled to make interesting considerations. Specifically, it has been found that several plantar pressure patterns perpetuated from pull to stand to confident walking stages, as the foot was progressively loaded in the attainment of independent locomotion, such as:

- The forefoot regions had a considerable involvement during stance phases of each motor task;
- The heel regions bore the greatest load;
- The lower pressure in the medial midfoot compared to the lateral;

For this reason, it has been argued that the typical pressure patterns establishing during stages of walking might be originating once the first form of upright bipedal locomotion, namely pull to stand, is performed. Descriptive analysis of plantar pressures however can just inform and provide insights regarding the typical plantar pressure patterns at each milestone, which can be only compared and integrated qualitatively to each other. To be able to establish the biomechanical characteristics of the foot in the transition to confident walking, changes in plantar pressures between milestones have also to be addressed also through statistical comparison. This would enable detection of specific and localised pressure changes that would strengthen the information capture in this chapter, thereby introducing novel insights about typical foot biomechanics that would enable to consider comprehensively foot function characteristics and development of the infant weight bearing foot. Therefore, the following chapters focussed on performing statistical comparison of plantar pressure data between stages of walking to inform specific foot-ground interactions changes taking place in the transition to confident walking.

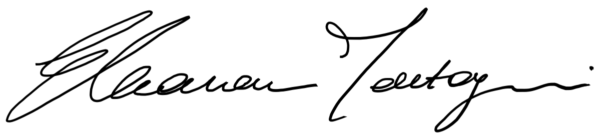
Chapter 6. Investigating typical patterns and changes of foot-ground interactions in infancy through vector fields analysis of centre of pressure

This chapter has been submitted as a standalone manuscript to the Journal of Biomechanics and it is currently under review as:

Montagnani E., Morrison SC., Price C., (2022). A vector field analysis to investigate foot-ground interactions in infancy during walking. *Journal of Biomechanics.*

I made the principle contribution in the conception and design of the study, analysis and interpretation of the research data and the drafting and critical revising of the final manuscript. Tables and figures are reported exactly as in the paper.

Dated: 26.07.2022

Signed: 

Eleonora Montagnani

6.1 Introduction

In the previous chapter, analysis of regional data described important characteristics of plantar pressures at different stages of motor development, with some patterns being present from pull to stand to confident walking stages. Given this novel information, comparison of plantar pressure data between stages of walking could increase understanding of the changes in foot function taking place with more walking experience. As part of this robust analysis to understand foot function development in infancy, the use of centre of pressure (COP) is a key component of plantar pressure data analysis, as it allows researchers to explore typical patterns as well as changes in the application of pressure that could highlight improved foot-ground interactions during establishment of independent and confident walking.

COP is defined as the point application of the ground reaction force or pressure vector during a step cycle (Cornwall and McPoil, 2000, De Cock et al., 2008), characterised by magnitude and direction properties (Rhea et al., 2014). Exploratory developmental studies investigating typical pressure application with respect to stance and its changes in infancy are scarce. For example, a few studies described, qualitatively, COP trajectories and their changes throughout the plantar surface of the foot during the first months after the onset of independent walking, reporting changes in foot contact patterns with more walking experience (Hallemans et al., 2003, Bertsch et al., 2004). Later, Hallemans et al. (2006b) carried out a more detailed investigation of the COP by analysing its medio-lateral (ML) and anterior-posterior (AP) components. However, they analysed COP data in the form of stability indices, defined as the sum of consecutive point application of the COP path, normalised by foot length (for AP trajectories) and width (for ML trajectories). In addition, a relatively recent study categorised, by visual observation, the types of contact patterns made in the transition to confident walking, and reported the characteristics of the COP according to the types of contact patterns identified (Zeininger et al., 2018). Such investigations were however limited to small samples, and prevalence of visual COP observation over analytical approaches that, however, discretised the ML and AP components of the COP. As a result, analysis of vector fields has been simplified and COP trajectories have not been treated in their continuous domain, thereby sacrificing data resolution, hence interpretation.

In addition, previous works in infants did not consider additional variables that could be calculated through COP analyses during walking, such as COP mean path lengths and velocity, which have the potential to enforce results from continuous analysis and increase knowledge related to how infants place their foot towards the ground in early stages of gait development. Therefore, this work aimed to explore pressure application and its changes during stance in the transition from the walking onset to confident walking stage. This was achieved by implementation of a robust framework for data processing of the ML and AP components of the COP, associated with high-resolution continuous data analysis using Statistical Parametric Mapping (SPM). Such analysis was performed alongside calculation of parameters related to COP and its component such as ML and AP mean path lengths and velocity, in order to offer a detailed account of foot-ground interactions changes as walking experience increases.

6.2 Research question

1. Do medio-lateral and anterior-posterior trajectories, mean path lengths and velocities differ from the onset of walking to confident walking?
2. If present, when in stance changes in medio-lateral and anterior-posterior trajectories are detected?

6.3 Methods

A full account of the materials, methods and ethical approval used in this work have been extensively reported in chapter 3. Therefore, a brief description was given below.

6.3.1 Design

This work is a repeated measure design reporting description, statistical comparison, and interpretation of medio-lateral and anterior-posterior components of the COP as infants becomes confident in walking.

6.3.2 Participants

Participants with pressure data set for the onset of walking (V2) and confident walking (V3), from both the University of Brighton and Salford, were used for this work. Infants were able to participate if they were born full-term, without impairment in attaining walking stages or gross motor development deficiency. Infants were excluded if diagnosed, had history of or were referred to consultation for neurological or musculoskeletal conditions.

6.3.3 Testing procedure

The testing procedure took place at University of Brighton and Salford, and parents had to attend each visit within 21 days since the attainment of the milestones, or they were excluded from the analysis. Milestones were defined as the onset of walking (V2) and confident walking (V3).

During each visit, plantar pressure data was collected using a Novel EMED xl platform (Novel, Munich, Germany), collecting at 100 Hz and with a sensor resolution of 4 sensors per cm^2. Videos were also recorded at each visit using a Vicon HD Camera (University of Brighton: Vicon Bonita 720c; Oxford, U.K/ University of Salford: Logitech HD Pro Webcam). The platform was placed in a nursery-style environment, and embedded in a soft mat, to ensure safety during testing (Figure 7). Infants were able to walk freely, to the extent of their abilities, at self-selected speed and in self-directed directions. The pressure system was triggered once infants initiated to walk, for 60 seconds. Detailed description of the three visits is reported in chapter 3.

6.3.4 Data processing

6.3.4.1 Pressure data extraction

As for chapter 4, section 4.3, left and right steps were obtained from the walking trials using the 'define period tool' in the standard EMED software (Novel, Munich, Germany). Subsequently, each step within the selected frames was extracted singularly using the manual 'select free line tool' from the standard EMED software and saved. Only steps originating from walking in straight lines (chapter 3) were included in the analysis. Steps were included in the COP processing framework only if they were taken within the platform borders and did not show missing of extensive anatomical parts. Stance phases of each step were also checked to ensure processing of steps from full walking cycles.

6.3.4.2 Centre of pressure processing framework

Data processing occurred exclusively in Matlab 2019a (The Mathworks Inc, Natick, USA) and followed several phases that have been reported below.

1. Frames of pressure extraction and pre-processing

For this work, the individual frames composing a pressure step were used for processing and analysis, as opposed to maximum pressure pictures (MPP) (chapter 4, section 4.3). Frames of pressure were obtained if a minimum of 10 kPa to a maximum of 1270 kPa were recorded. All the frames contained within each pressure step of the left and right steps were exported as ASCII text files using the Novel Emascii software and imported into Matlab as 2-dimensional (2D) numeric matrices. Non-zero entries of the frame matrices corresponded to pixels containing pressure values. A final amount of 16.488 and 14.881 frames for left and right feet, respectively, were included in the processing framework. Each frame was then positioned in a grid of 36x25 pixels, to standardise frames' matrix dimensions and create a common reference system among all the intra and inter-individual frames.

Because different orientation of the frames in the Euclidean space would affect the computation of AP and ML component of the COP, sets of frames for each participant and each step in both visits were vertically rotated using principal component analysis (PCA). Specifically, a frame template (selected as the frame with the highest number of pixels within its matrix) was chosen for each set of pressure steps and participant in both visit. Next, PCA was performed following the phases of work described in chapter 4, section 4.3. The aim was to identify the principal axes of the images (feet), and calculate the angle (ϴ) required to perform a counter clockwise rotation to vertical of the template frame (Figure 15). The angle obtained was then applied to each frame of the same step to perform a consistent rotation of the data. This was achieved by using a built-in Matlab function ("imrotate") to rotate each frame of both left and right feet of V2 and V3 in a custom-made script, where rotated frames were also cropped to the original matrix size (36x25).

2. Computation of centre of pressure trajectories

Once all the frames of each participant at the two visits were consistently oriented in the Euclidean space, a 3-dimensional (3D) structure (36x25xlength of the amount of frames contained in each step) was created in a custom-written Matlab script. Next, a Matlab function provided by Rashid et al. (2019) was used (https://github.com/GallVp/footPress) to compute COP trajectories out of the 3D structure. The function calculated the coordinates of the centroid of each frame, returned as a 2-by-Q matrix, through weighted averages, where the first element was the horizontal coordinate (or x-coordinate), and the second element is the vertical coordinate (or y-coordinate). The x and y coordinates of the COP represented the ML and AP components of the COP respectively, which were treated as separate vectors ML (t) and AP (t):

$$\text{COP}(t) = [\text{ML}(t)\ \text{AP}(t)]$$

Where t represents the time domain. Distinguishing between the two components of the COP was essential as ML and AP time series demonstrated distinct characteristics (Winter, 1993), which supports the choice to analyse the COP in its independent dimensions.

3. Spline interpolation of COP trajectories

New ML and AP components of COP trajectories were obtained using a built-in Matlab function for spline interpolations ("spline"), and 101 points, defined as the total stance phase, were sampled on such interpolants. This enabled temporally normalisation of the COP trajectories, ensuring the data was arranged correctly for statistical comparisons.

4. Creation of reference system for medio-lateral and anterior-posterior component

Once 101 were sampled, within-infant ML and AP trajectories were estimated for each infant and for both visits. Whilst with PCA, frames of pressure steps were consistently oriented in the Euclidean space, differences were still present as to where in the matricial reference system (36x25) those frames were positioned across participants and walking stages. Therefore, a common matricial reference system for the respective components of the COP was also created across participants. This procedure was undertaken using the complete pressure images (feet) of each participant.

For ML, the longitudinal axis of each image (foot), defined as a straight line starting from the middle of the heel to the middle of the second toe, was estimated through PCA. The longitudinal axis of each foot passed through the image centroid (J), which was identified for each complete pressure step of each participant at both visits (Figure 24, pink star). A within-infant centroid (J_{Wi}) was calculated across the set of images at each visit and used to estimate the between-infants centroid (J_{Bi}) across visits. Such value was then used to calculate new entries of the within-participant ML trajectories, namely:

$$\text{ML}_i(t) = \text{ML}(t) - J_{Bi}$$

Equation 7. Calculation of new entries of within-infant medio-lateral (ML) trajectories for inter-individual data comparison.

Then, the resulting within-participant ML trajectories were converted in cm to facilitate interpretation. As a result, points' applications of the within-infants ML trajectories with negative and positive values (thus falling on the left and right of the longitudinal axis of the image (foot)) were considered as lateral and medial point COP applications, respectively. For AP, the most posterior contact point of each step (Figure 25, pink star) was determined by considering the minimum value of the matrices reference system in the y-axis, given that each image was contained in a 36x25 grid of pixels. Such point, defined as K, was then averaged within-infant (K_{Wi}) and then a between-infants value was estimated (K_{Bi}) to calculate new entries of the within-infant AP trajectories in both visits.

This was achieved with:

$$AP_i(t) = AP(t) - K_{Bi}$$

Equation 8. Calculation of new entries of within-infant anterior-posterior (AP) trajectories for inter-individual data comparison.

As for the ML trajectories, the resulting intra-individual AP trajectories were converted in cm to facilitate data interpretation.

To enhance visualisation and interpretation of AP and ML pressure application patterns in the real foot anatomical correspondence, a template image has been generated and will be add to the results figures (see Results section). For AP, the template was chosen as the image (foot) with the most posterior point of contact (K) found with respect to the y-axis of each image, between participants and visits. For ML, the same image template of the AP trajectories was used for consistency, but the centroid of the image was identified by plotting the mean centroid (JBS) across infants onto the image.

Figure 24. Example of longitudinal axis of the feet passing through the estimated centroid (pink star) of each image (foot).

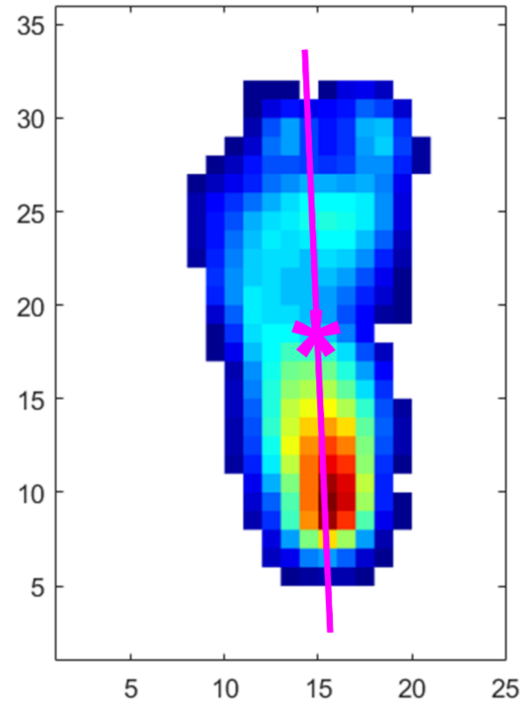
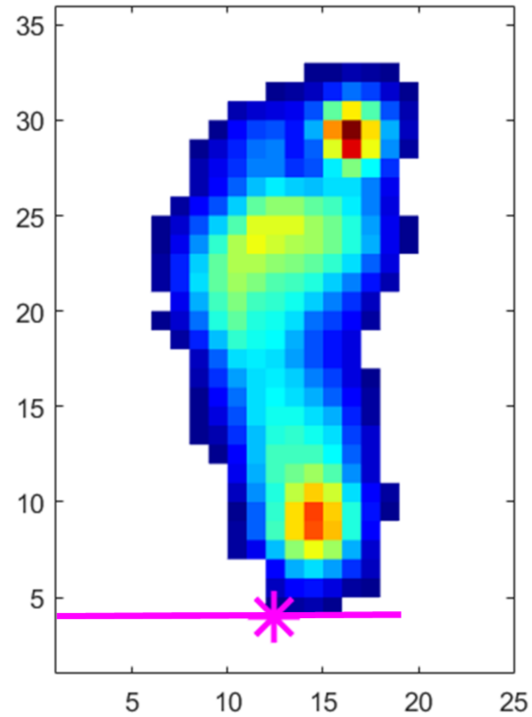


Figure 25. Example of the minimum value of the y-axis (pink star) of the matrices representing the most posterior point of each image (foot).



5. Calculation of COP path length and velocity

To increase understanding of the COP changes in the transition to confident walking stage, mean total path lengths of the ML and AP trajectories were also calculated according to Quijoux et al. (2021). Specifically, ML (t_x) and AP (t_y) mean total path length of the COP were computed as:

$$\sum_{x=1}^{N-1} t_x = \sqrt{(x_{i+1} - x_i)2}$$

$$\sum_{y=1}^{N-1} t_y = \sqrt{(y_{i+1} - y_i)2}$$

Equation 9. Calculation of mean path lengths of the medio-lateral (top) and anterior-posterior (bottom) trajectories.

The numerical values were converted in cm to enhance data analysis and interpretation. Once ML and AP path lengths were identified, their respective mean velocity over the stance phase (V_x and V_y) were also calculated according to the following formulas:

$$\sum_{x=1}^{n} V_x = \left|\frac{x_{i+1} - x}{T}\right|$$

$$\sum_{y=1}^{n} V_y = \left|\frac{y_{i+1} - y}{T}\right|$$

Equation 10. Calculation of mean velocities of the medio-lateral (top) and anterior-posterior (bottom) trajectories.

As described by Quijoux et al. (2021), given a constant sampling frequency, V_x and V_y were defined as the sum of the distances between consecutive points, expressed as ML and AP lengths of the COP (cm), divided by the duration of the stance (T seconds). Calculation of the mean velocity variables will give a numeric value expressed in cm/s, which will be interpreted as the mean distance (in cm) travelled in each second by the COP directions.

6. Normalisation to foot length and width

As a final phase of data processing, both ML and AP trajectories as well as mean path lengths and velocities of each infant were normalised to the respective feet lengths and widths, to account for differences between lengths and widths of the infants' feet at each walking stage, and thus allowing further comparison.

6.3.5 Data analysis

Vector fields' analysis of the COP trajectories was conducted in custom-made Matlab scripts, whilst discrete analysis of mean path lengths and velocities was carried out in the SPSS software (IBM Statistics, version 25). In general, data analysis started as for chapter 5, thereby comparing COP data of both left and right feet as a general requirement to allow correct interpretation of COP data. As a result, COP trajectories and mean path lengths and velocities were calculated for each left and right step. Because the nature of the full COP trajectories was different from discrete variables (ML and AP trajectories were 1-dimensional (1D) whilst path lengths and velocities were 0-dimensional (0D)), statistical analysis between feet was carried out differently for (i) the trajectories and (ii) path lengths and velocity.

(i) ML and AP trajectories of left and right feet were compared within each visit using the nonparametric SPM1d paired t-test in Matlab. Comparison of left and right COP trajectories at each visit revealed the absence of significant differences (Appendix 3, Figure 38, 39, 40 and 41), and thus COP trajectories from left and right feet were combined for each participant, increasing the data sample. To do so, frames of the right feet were mirrored to the left feet using a built-in Matlab function ("fliplr") that enabled to flip the matrices of the right frame to the left. Prior to undertaking statistical comparison of COP trajectories between the two visits, absolute and normalised data were checked for normality using the SPM1d normality test for 1D data (http://www.spm1d.org/). Normality tests failed to reach significance at alpha=0.05, suggesting insufficient evidence against the null hypothesis of normality (Appendix 4, Figure 43, 44, 45 and 46). Thus, a parametric paired SPM1d t-test was used to account for localised differences across stance phase ML and AP trajectories between V2 and V3, with significance set as $\alpha=0.05$.

(ii) With respect to ML and AP mean path lengths and velocities, absence of differences between left and right feet at each visit was found ($p>0.05$) (Appendix 3, Table 13).

Therefore, ML and AP path lengths and velocity were combined between feet of each participant and compared between infants at the onset of walking and confidently walking. Data was firstly checked for normality using the Shapiro-Wilk test (Ogunleye et al., 2018). Because data was not normally distributed (Appendix 4, Table 14), data were compared between visits using the Wilcoxon Signed Ranks test ($p<0.05$). As for the ML and AP trajectories, this work reported absolute and normalised values of mean path lengths and velocities normalised to participants' feet lengths and width for AP and ML values, respectively. Descriptive statistics in the form of median and 25th and 75th quartiles values were reported, to account for boundaries of normality in the data.

6.4 Results

In this work, 39 infants (20 females) were included in the analysis, as they had attended both V2 and V3. Demographic characteristics of the sample are reported in table 8.

Table 8. Sample demographics of Chapter 6.

	Onset of walking (V2)				Confident walking (V3)			
Measures	**Min**	**Mean**	**SD**	**Max**	**Min**	**Mean**	**SD**	**Max**
Age at visit (months)	9.1	13.3	1.6	16.6	12.3	15.6	1.8	20.2
Age at milestone (months)	8.6	12.8	1.5	16.2	11.8	15.1	1.8	19.6
Days since milestone (days)	7.0	14.5	5.1	21.0	3.0	15.2	5.5	21.0
Mass (kg)	8.0	10.3	1.3	13.8	8.5	11.0	1.3	14.0
Height (cm)	68.5	74.7	3.1	81.8	71.9	78.4	3.5	85.0
Foot length (cm)	9.7	11.4	0.7	12.6	10.5	11.9	0.8	13.6
Foot width (cm)	4.4	5.2	0.4	6	4.3	5.2	0.4	6.2

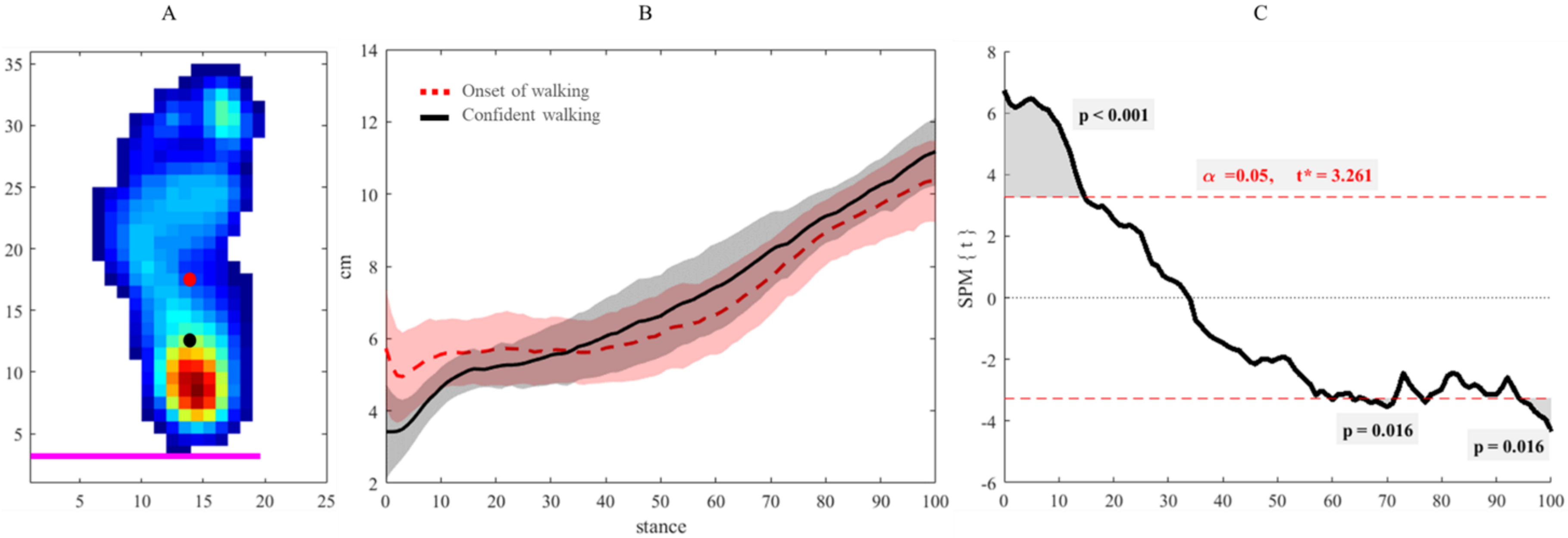
6.4.1 Pressure data overview

The absence of significant differences between left and right COP data allowed statistical comparison to occur using a larger data sample, resulting in analysis of three steps for each foot, for each participant at each visit (3 steps *2 feet *39 participants *2 visits), for a total of 468 steps and 31,369 frames of pressure analysed. Once pressure data of left and right feet were combined and processed, statistical comparison of the full COP trajectories, mean path lengths and velocities was carried out at the onset of walking and confidently walking.

6.4.2 Anterior-posterior trajectories

Mean and standard deviation (SD) figure of absolute AP trajectories (Figure 26, B) demonstrated that pressure was distributed at initial loading more posteriorly in V3 compared to V2. Specifically, origin of the AP trajectories at V2 was found at 6 cm from the most posterior contact point of the feet (Figure 26, A, magenta line), which was identified as a mean initial loading within the midfoot (Figure 26, A, red dot). Alternatively, the origin of the AP trajectories in V3 was located at 3.5 cm from the most posterior contact point of the feet, which was located in the heel (Figure 26, A, black dot). From 40% of stance, the AP trajectory of confident walking infants was more anterior by almost 1 cm compared to infants at the onset of walking. The red shade around the mean AP trajectory of V2 demonstrated high SD, hence large inter-individual variation of pressure application at initial loading from 0 to 15% of the stance at the onset of walking, approximately. In the same period of stance, SD of infants confidently walking was reduced, with similar decreasing variation present between 80 and 100% of the stance. Similar descriptive characteristics were present also considering the normalised AP trajectories to foot lengths (Figure 27, A). However, from 40% of stance, the normalised AP trajectories of infants at V2 and V3 followed the same path towards end of the stance and almost overlapped perfectly. Statistical analysis of absolute and normalised AP trajectories between V2 and V3 identified the presence of significant differences between 0 and 20% of stance (absolute; $t=3.01$, $p=0.001$) (Figure 26, C) and 0 and 25% of stance (normalised; $t=2.97$, $p=0.001$) (Figure 27, B). However, differences in descriptive data between absolute and normalised AP trajectories are reflected in the statistical results. Accordingly, SPM analysis revealed the presence of significant differences between V2 and V3 from 60 to 70% ($t=2.97$, $p=0.001$) and from 95 and 100% of stance ($t=2.97$, $p=0.001$) (Figure 26, C). Such differences were not detected between V2 and V3 in the normalised AP trajectories (Figure 27, B).

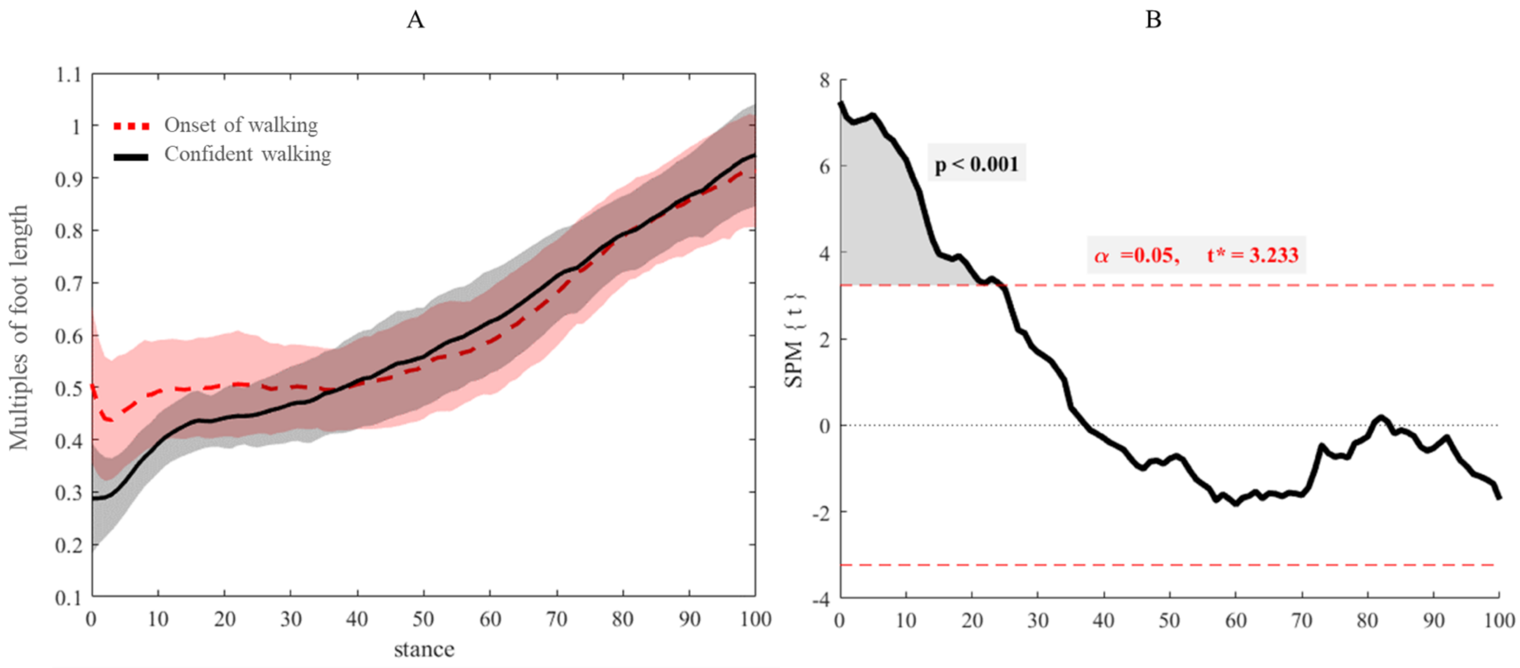
Figure 26. (A) Anterior-posterior (AP) template chosen between-infants as the pressure image with the most posterior point of contact (identified using the parallel magenta line to the x-axis) in the matricial reference system. (B) Mean (cm) and standard deviation (shades) of absolute anterior-posterior (AP) trajectories of infants at the onset of walking (red dashed line) and confidently walking (black line), temporally normalised to 101. (C) Parametric SPM1d paired t-test for comparison of the anterior-posterior COP trajectory between V2 and V3.



[7]

[7] The origins of the AP trajectories have been identified with the magenta line. Critical threshold was exceeded between 0-20, 60-70 and 95-100% of stance, indicating a significantly increase in posterior loading in confident walkers.

Figure 27. (A) Mean and standard deviation (shades) of normalised anterior-posterior (AP) trajectories to feet lengths of infants at the onset of walking (red dashed line) and confidently walking (black line). (B) Parametric SPM1d paired t-test for comparison of the normalised anterior-posterior COP trajectory between V2 and V3.



[8]

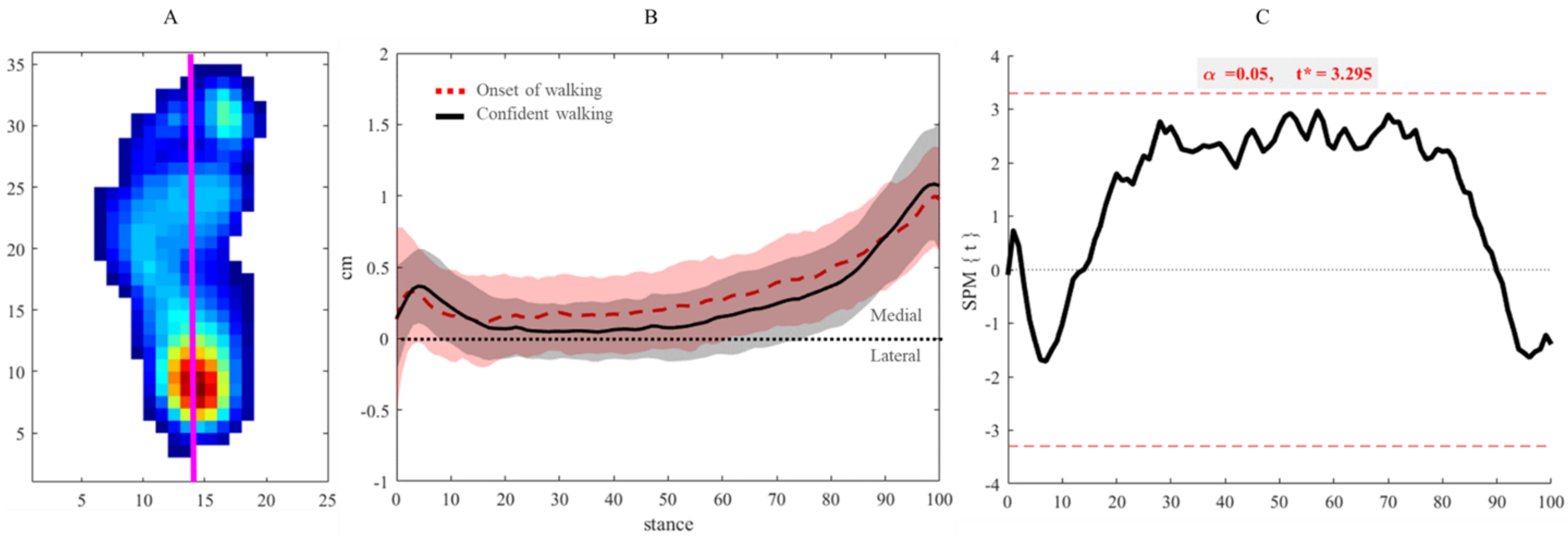
[8] The y-axis of the image represents the percent of foot length with respect to one, being the total foot length. Critical threshold was exceeded between 0-25% of stance, indicating a significantly increase in posterior loading in confident walkers.

6.4.3 Medio-lateral trajectories

Mean and SD of absolute ML trajectories showed that infants in both V2 and V3 applied pressure onto the medial side of the foot between 0 and 20% of the stance approximately (Figure 28, B). From 20 to 85% of stance, infants at V2 demonstrated a more persistent medial loading application in comparison with infants at V3. In fact, the COP trajectory of confident walkers was closer to the longitudinal axis of the foot (Figure 28, B, dashed line). From 60% of the stance, pattern of medial pressure application of was again present, peaking between 80 and 100% of stance. These descriptive characteristics were almost the same reported in the normalised ML trajectories to the infants' feet widths (Figure 29, A). However, from 20 to 85% of stance, differences in medial loading between V2 and V3 were more accentuated.

Despite changes of medio-lateral loading from the onset of walking to confident walking were present, SPM analysis revealed no significant differences between V2 and V3 of both absolute ($t=3.26$, $p>0.05$) (Figure 28, C) and normalised ($t=2.95$, $p>0.05$) ML trajectories (Figure 29, B).

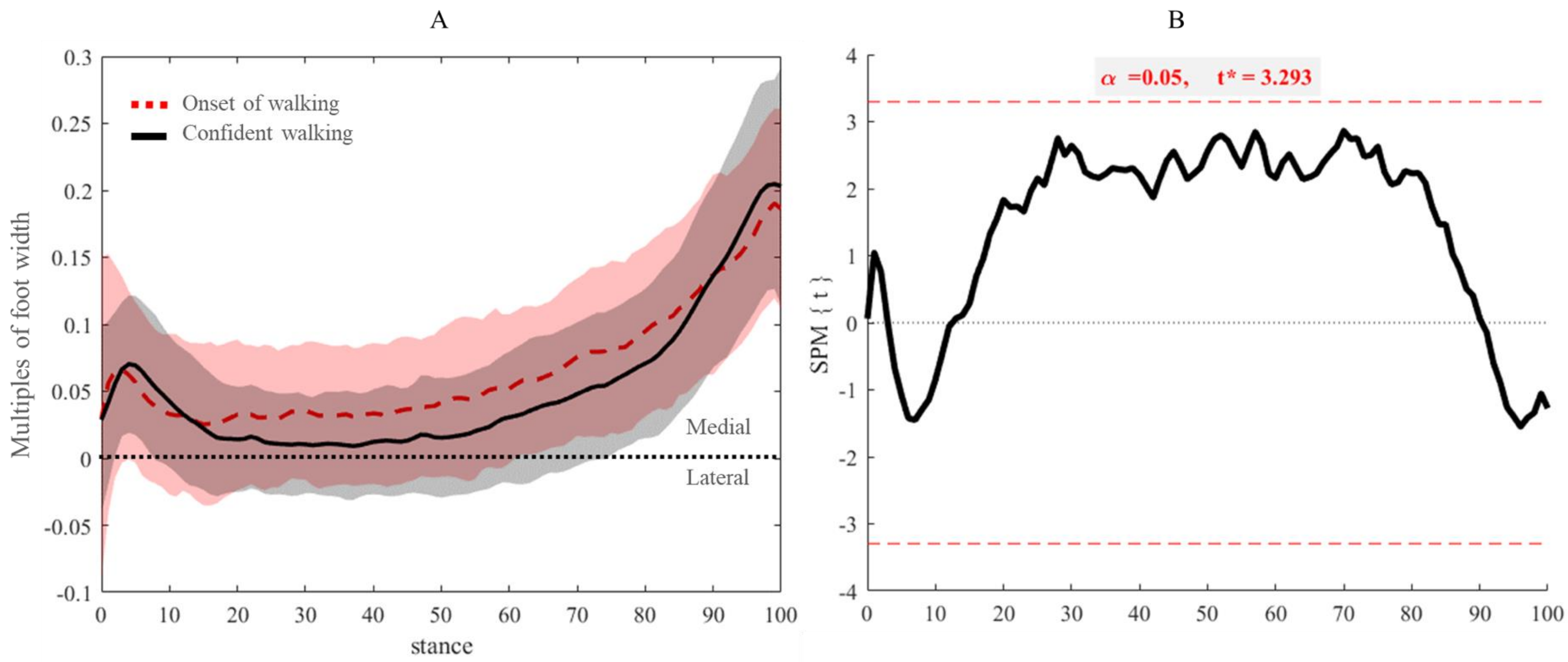
Figure 28. (A) Medio-lateral (ML) template. This has been selected to be consistent with the anterior-posterior template, but the longitudinal axis (magenta line) has been estimated between-infants, representing the black dashed line in B. (B) Mean (cm) and standard deviation (shades) of absolute medio-lateral (ML) trajectories of infants at the onset of walking (red dashed line) and confidently walking (black line), normalised to 101. (C) Parametric SPM1d paired t-test for comparison of ML components of the COP trajectory between V2 and V3.



[9]

[9] Magenta line represents longitudinal axis calculated across all the pressure data. Critical threshold was not exceeded across any point in stance, indicating absence of statistical differences.

Figure 29. (A) Mean and standard deviation (shades) of normalised medio-lateral (ML) trajectories to feet widths of infants at the onset of walking (red dashed line) and confidently walking (black line). (B) Parametric SPM1d paired t-test for comparison of ML components of the COP trajectory between V2 and V3.



[10]

[10] Critical threshold was not exceeded across any point in stance, indicating absence of statistical differences.

6.4.3 Mean path length and velocities of centre of pressure trajectories

With respect to AP, absolute mean path length decreased from 14.9 to 12.1 cm, which was also reported as a significant decrease from the stage of the onset of walking to confident walking (Z=-3.775; p=0.001). A large variation around the median was also present in V2, which evidently reduced, as infants became confident walkers. Normalised mean path length of the AP trajectory decreased by almost 1/3 of the foot length from the onset of walking to confident walking, which was also found to be significant (Z=-3.993, p=0.001). The normalised AP mean path length also demonstrated lower variation around the mean in comparison with absolute values, in both visits. AP mean velocity demonstrated an increased from 22.6 cm/s to 25.7 cm/s, which was significant (Z= -3.489; p=0.001). This significance was found also for the normalised measure (Z= -2.615; p=0.009). Absolute AP mean velocity demonstrated a large variation in both visits, which reduced when normalised.

With respect to ML, absolute mean path length decreased by 0.9 cm from V2 to V3, with reduced variation around the median from V2 to V3. Such a change was also found to be significant (Z=-3.781; p=0.001). Normalised ML mean path lengths also significantly decreased from V2 to V3 (Z=-3.932; p=0.001).The absolute ML mean velocity at V2 was 5.7 cm/s, increasing by 1 cm/s in V3. As for AP mean velocity, the data demonstrated larger variation in V3 compared to V2. Statistical comparison of ML velocity between stages of walking also identify significant changes in both absolute (Z= -2.212; p=0.02) and normalised measure (Z= -2.103; p=0.03).

Table 9. Descriptive characteristics of anterior-posterior (AP) and medio-lateral (ML) path lengths and velocities.

	Stages of walking	Descriptives		AP mean path length	ML mean path length	AP mean velocity	ML mean velocity
Absolute values (paths expressed in cm and velocity in cm/s)	**Onset of walking (V2)**	**Median**		14.9	4.2	22.6	5.7
		Quartiles	**25**	13.3	3.3	19.3	4.4
			75	17.2	5.5	26.1	7
	Confident walking (V3)	**Median**		12.1**	3.3**	25.7**	6.7*
		Quartiles	**25**	10.9	2.8	22.7	5.4
			75	13.6	3.5	31.3	7.8
Normalised values (multiples of foot length and width)	**Onset of walking (V2)**	**Median**		1.3	0.8	2	1
		Quartiles	**25**	1.2	0.6	1.8	0.9
			75	1.6	1	2.3	1.4
	Confident walking (V3)	**Median**		1**	0.6**	2.2*	1.3*
		Quartiles	**25**	0.9	0.5	1.9	1
			75	1.2	0.7	2.5	1.4

** *p=0.001;* **p=<0.05*

[11]

[11] Absolute mean velocity and path length values are expressed in cm/s and cm, respectively. Normalised mean path lengths and velocities are expressed as multiples of foot length and width for AP and ML values, respectively. The stars represent values that demonstrated a significant change from V2 to V3.

6.5 Discussion

This chapter of the thesis aimed to report, for the first time, analysis, and interpretation of continuous and discrete COP data to enhance understanding of foot-ground interactions in the transition to confident walking, providing detailed and novel insights into plantar pressure application and its changes over stance in infancy. Below, results of AP and ML components of the COP trajectories will be discussed in two sub-sections, respectively.

6.5.1. Anterior-posterior changes

At the onset of walking, the present work demonstrated that the midfoot region was the primary interface with the ground at initial loading, with large inter-individual variation in the first 15% of stance. This suggested that initial contact patterns varied from heel contact to midfoot and forefoot contact, thereby reporting inconsistent initial loading patterns among infants at the onset of walking. In an earlier observation, the presence of different contact patterns at initial contact has been also reported, but infants at the onset of walking showed prevalence of forefoot contact at initial loading, followed by whole-foot contact (defined as the heel, midfoot and forefoot making contact with the ground simultaneously) and heel contact (Hallemans et al., 2003).

Some considerations to explain differences in results between the present chapter and previous work are therefore needed. For example, Hallemans et al. (2003) did not specified the age of infants when data was firstly captured, and thus they might have been younger of the sample observed in this chapter, demonstrating different loading patterns. In addition, Hallemans et al. (2003) described the COP trajectories through visual observation, to speculate about loading application across the foot, without calculating and quantifying changes occurring in the AP direction specifically. Accordingly, the initial point application of the COP is the mean location of pressure calculated across the loaded sensors of the first frame of the images analysed. Calculation of such pressure application might provide more specific results than visual estimate throughout the plantar surface of the foot. Absence of quantitative analysis, therefore, possibly led to subjective data interpretation and generalised information related to initial pressure application. Finally, the study used a platform with a sensor resolution of 3.5 sensors per cm^2, whilst data in this work was collected using a pressure platform with 4 sensors per cm^2, which possibly enabled to capture more precise pressure information without missing important patterns of pressure application.

Despite these considerations, significant changes in the AP pressure application have been detected in the first 20-25% of stance approximately between infants at the onset of walking and confidently walking. This suggested changes of initial loading pattern between these stages. Accordingly, infants acquired more confidence in walking and the heel became the predominant initial contact pattern in V3, which is also supported by previous works reporting the presence of such pattern after few months of independent walking experience (Bertsch et al., 2004; Hallemans et al., 2003). The development of initial heel contact might be related to changes in lower limb posture in infancy. Specifically, one-year-old infants showed ankle plantar flexion at initial contact associated with decreased ankle dorsiflexion during swing that prevents the vertical position of the heel in relation to the ground (Price et al., 2018b). Hallemans et al. (2006a) demonstrated that after five months of independent walking experience, the knee is flexed and ankle is in dorsiflexion at initial foot contact. The increased ankle dorsiflexion leads the heel to contact the ground first during gait, denoting a change to a plantigrade foot pattern.

With changes in lower limb posture, it has also been demonstrated that co-contraction of anterior/posterior leg muscles (tibialis anterior and gastrocnemius) decreased after three months of independent walking experience (Chang et al., 2006, Okamoto et al., 2003, Teulier et al., 2012). A more efficient muscle activity has to be attributed to neuromuscular-skeletal development, whereby the growth of neural structures improves organisation and speed of neural signals, enabling infants to improve integration and processing of motor inputs (Adolph et al., 2003). As a result, activation of tibialis anterior in experienced walkers during swing is more accentuated than in infants who just started to walk, and this is likely also to enhance ankle dorsiflexion at initial contact (Assaiante et al., 2000).

Therefore, combination of improved muscles activity and changes in the ankle posture might explain why changes in initial loading patterns occur after 2.3 months of independent walking. Despite these considerations, there is lack of studies combining biomechanical data analyses (such as kinematic, electromyography, etc.) to understand why changes in pressure application over stance occur in the transition to confident walking, confirming that such factors should be identified as exploratory variables supporting changes in foot loading at initial contact, warranting further investigations.

With the presence of differences within the phase of initial loading during stance, the absolute AP trajectories of infants at the onset of walking and confident changed also in the latter parts of stance. In fact, from 60 to 100% of the stance, absolute AP trajectories of infants at V3 proceeded more anteriorly by almost 1 cm. Such pattern is likely due to the presence of foot lengths differences between infants at the two visits, which is in agreement with differences in foot lengths reported in Table 8 (+0.5 cm). In this context, the use of a high-sensor resolution pressure platform is important to allow capturing even the smallest alterations that are characteristic of this sample. The influence of differences between foot lengths on AP trajectories was supported by the statistical results obtained using AP trajectories normalised to infants' feet lengths. Accordingly, figure 27 showed that such differences were lost; specifically, the mean data almost demonstrated a perfect overlap of the AP trajectories, confirming that changes were due to differences between feet lengths as opposed to real functional differences. The use of normalised AP trajectories also helped demonstrate that the COP travelled the entire length of the foot during walking. Specifically, normalised trajectories reaching 100% of the total foot length demonstrated that the COP terminated the stance phase within the hallux or toes, which was also demonstrated by normalised mean AP path lengths (Table 9). In addition, normalised mean path length and velocity of the AP trajectory demonstrated lower variability in V2 and V3 compared to absolute values, with both quartiles being closer to the median in comparison with absolute values. This might highlight that once inter-individual differences in feet lengths were mitigated, variations of the AP mean path lengths and velocity reduced, supporting the importance of normalisation to inform meaningful outcomes from applications of plantar pressures and their changes in infancy.

Changes within the AP trajectories occurred alongside significant decreasing path lengths and significant increasing AP mean velocity of the COP from the onset of walking to confident walking stages. Considerations related to changes in the AP path lengths can be made by appreciating the initial contact patterns of the AP trajectories in V2 and V3. As an example, with initial loading being detected in the midfoot area in V2, the AP trajectories passed from an anterior position at first contact (midfoot) to a posterior one when the heel touches the ground, following a pattern of anterior application of pressure as infants move forward and prepare to push off. Reasonably, such changes led to longer path of the AP component of the COP, as larger forward-backward oscillations of the COP were present at this stage due to immature foot-ground interactions at the onset of walking, increasing the distance travelled by the COP during gait. Long path length of the AP trajectories in V2 were associated with low mean AP velocity of the COP, which increased in V3. As a result, the backward to forward progression of the COP was quicker in confident walking stage. This would also be consistent with findings associated with contact time values of pressure data reported in chapter 5, which showed that infants' contact times relative to the stance decreased as infants became more confident in walking.

6.5.2 Medio-lateral changes

With respect to the ML trajectories, infants in both visits demonstrated the presence of a medial pressure application between 0 and 15% of stance approximately. In the previous paragraph, this event of stance was identified as part of the initial foot-loading phase based on existing literature. With this information, it is possible to say that the phase of initial loading in V2 and V3 occurred medially.

From the end of the initial loading phase, (20% approximately of stance), it is possible to surmise the beginning of the whole-foot contact phase. From 20 to 70% of this period, infants at the onset of walking and confidently walking demonstrated medial pressure application. This would be in agreement with chapter 5, where it has been reported that the medial regions of the foot were subject to highest pressures than the laterals in both visits. It is interesting to notice that individuals with chronic ankle instability also showed a more medial COP position during walking (Simpson et al., 2020). There is absence of similar data in infancy to draw comparison with and there are differences between the biomechanics of adults affected by chronic ankle instability and the infants in this chapter, and thus considerations in this context have to be made with care. Nevertheless, it is plausible to say that the high laxity characteristics of the infant's musculoskeletal system might allow wide ranges of movement at the ankle, which results less stable than in adulthood, for example, when the musculoskeletal structures are fully developed.

These musculoskeletal characteristics of the infant might also explain the long ML mean path length demonstrated at the onset of walking, as the large degrees of freedom during walking likely caused infants to increase ankle compensatory movement in the frontal plane. Such ankle movements can be seen as attempts of infants to balance out the application of pressure on the plantar surface of the foot during a step cycle, actuating strategies at the ankle to compensate its lack of stability and control, avoiding falls as well as loss of balance while progressing forward. The significantly reduced ML mean path lengths in confident walkers illuminate the presence of less erratic patterns of medio-lateral pressure application on the plantar surface of the feet, which has been also demonstrated in previous work (Hallemans et al., 2006b). This could therefore highlight the reduced amount of ankle movements in the frontal plane, hence a more controlled foot placement during walking.

With a more controlled foot placement during walking, infants are therefore able to explore novel patterns of pressure application across the foot during stance. Accordingly, the main differences between the two stages of walking were detected between 20 and 70% of the stance, where infants in V3 recorded application of pressure that was closer to the longitudinal axis of the feet. A relatively recent analysis of COP data in adulthood showed that at self-selected speed, pressure was applied laterally after initial loading (Pataky et al., 2014). Therefore, it is possible to say that foot-ground interactions changed towards a more mature pattern of plantar pressure application. This is also visible after 70% of stance, when pressure is increasingly applied medially in both visits, suggesting that the terminal phase of stance, the hallux was used to push off as it occurs in mature walking (Pataky et al., 2014, Safaei-Pour et al., 2009). Such consideration is possible as the reference system used to visualise pressure application changes considered the longitudinal axis of the foot passing from centroid of the foot, with the hallux remaining on its medial side. In addition, the normalised AP trajectories demonstrated that the COP travelled the entire length of the feet during walking. By combining these information, it is therefore possible to say that the phase of foot-off was achieved using the hallux, which was not investigated in earlier infants' biomechanical research.

Development of foot-ground interactions were also demonstrated by significant changes of the ML mean velocity of the COP. Accordingly, both absolute and normalised ML mean velocity in V2 were lower compared to V3. Such pattern could suggest that infants at V2 demonstrated a slow recover of the medio-lateral COP displacement during walking, describing poor postural control. As ML mean velocity increased, infants did not need prolonged time to recover the medio-lateral COP displacement, highlighting a more efficient pattern of pressure application. This might be associated with the development of the anticipatory postural adjustment mechanism, whereby infants developed the ability to anticipate the presence of internal perturbation caused by voluntary movements (such as walking) (Westcott and Burtner, 2004), and thus suggesting improved postural control. Differently from other variables, variations in the data of ML velocity was higher in V3 as opposed to V2, and this was present mainly in the upper quartile. This might be explained as infants attended data collection as confident walkers within a different window of time

(Table 8). For example, the days waited by infants to being invited to the lab when they could confidently walk ranged between three and 21. Considering these differences, it is likely that infant within the same visit were also characterised by different walking abilities as they would have more or less walking practice, resulting in higher inter-individual ML velocity.

6.6 Limitation of the work

Despite the novelty of this work, interpretation of the results originating from ML and AP trajectory comparison between visits might be limited, as there is limited knowledge of the stance phase events in infancy. Such events are recognised in typically-developed individuals and are widely reported in the literature (Whittle, 2007, Stergiou, 2020), but not in the field of paediatric gait analysis. This could be due infants being characterised by ongoing development of gait, thereby demonstrating high intra and inter-individual variability in the use of the foot during stance, limiting identification of consistent stance phase events. Furthermore, the lack of combined biomechanical analyses (e.g., the concurrent use of EMG) as well as the inclusion of two stages of walking development as opposed to data acquisition of further improved walking stages can limit interpretation related to changes in the AP and ML component of the COP.

6.7 Summary and conclusions

With this work, important and novel information has been highlighted in relation plantar pressure applications and their changes based on a robust COP data analysis, which enabled to consider rapid and unique improvement of foot-ground interactions in infancy. Specifically, this work reported interpretation of stance phase events in infancy that were not investigated before and could lead future works to improve understanding of pressure application changes across stance. In this work, vector fields' analysis of the COP objectively demonstrated the presence of the following changes with more confident walking:

- A less accentuated medial pressure application as the whole foot was in contact with the ground;
- The establishment of initial heel contact;
- Push off with the hallux;
- Significant decreasing ML and AP path length and increasing velocity of the COP;

Such in-depth and early changes in pressure application were not reported before, although previous work quantified COP data in a similar group of infants (Hallemans et al., 2003; Hallemans et al., 2006b). In addition, this work highlighted, for the first time, important aspects of foot-ground interaction changes associated with lower inter-individual oscillations of the COP and increasing mean velocities in both AP and ML directions, supporting the presence of a more stable and controlled foot placement during walking. With respect to data related to mean path lengths and velocities of the ML and AP component of the COP, it has been challenging to explore the reasons as to why those changes occurred in the transition to confident walking, mainly due to the lack of research of the aforementioned variables in the field of paediatric COP analyses. Furthermore, the present work was undertaken by considering only COP data, without combining biomechanical data analysis or investigation of anatomical maturation of the foot and lower limb as foot-ground interactions changed. Such analyses are therefore warranted, as changes in pressure application over stance is clearly dependent upon changes in several body systems such as the neurological, musculoskeletal, and sensory systems. Based on these considerations, the next chapter will consider the relationship between factors associated with the overall body maturation and walking experience with plantar pressures, which has the potential to predict changes in peak pressures in the transition to confident walking.

Chapter 7. Exploring changes in plantar pressures and their relationship with body maturation and walking experience

7.1 Introduction

Chapter 6 demonstrated that, as infants become confident walkers they established initial foot contact with the heel as opposed to the midfoot, less accentuated medial loading after first contact phase, initial and terminal medial loading, as well as a more controlled foot placement on the ground. In combination with these findings, analytical comparisons of the amount of pressure applied onto the plantar surface of the foot between stages of walking development have the potential to provide important results related to foot function changes. Nevertheless, analysis of plantar pressures has been mainly carried out with traditional approaches to masking analysis in infancy (Bertsch et al., 2004; Bosch et al., 2010; Hallemans et al., 2003; Hennig and Rosenbaum, 1991), and the limitations of which have been extensively reported within this thesis. Accordingly, chapter 4 validated the use of pedobarographic Statistical Parametric Mapping (pSPM) (Pataky and Goulermas, 2008), where a sample of 12 infants was analysed to test robustness and the applicability of this approach within this sample. However, a more detailed account of changes in pressure from a larger sample in the transition to confident and independent walking using pSPM has not been reported yet.

In addition, there is scarcity of studies predicting plantar pressure changes variables related to body maturation and increasing walking experience to changes in plantar pressures in infancy. Accordingly, only Bosch et al. (2010) analysed the relationship of body weight and height with plantar pressures. To further advance this work, other variables could be used for this purpose, such as the increasing foot length and foot width, that have not been accounted for in previous works predicting plantar pressure changes in the transition to confident walking. Furthermore, Bosch et al. (2010) used discrete statistical analysis for predicting changes in pressure. Using continuous statistical analyses to perform such investigation could be important, as it would enable the detection of exact foot locations where certain variables would be associated with changes in pressure. Therefore, the aims of this study were to compare plantar pressures of infants at the onset of walking and confidently walking, and to establish the relationship of maturation factors (body weight, height, foot length and foot width) as well as walking experience to plantar pressure with continuous statistical analyses.

7.2 Research questions

1. Are there changes in plantar pressure between new and confident walkers?
2. Where do changes in plantar pressure occur within the foot?
3. Is there a significant relationship between variables related to body maturation (body weight, height, foot proportions, foot length, and foot width) and walking experience with plantar pressures in the transition to confident walking?

7.3 Methods

As for the previous chapter, details about materials, methods and ethical approval used in this work have been extensively reported in chapter 3. Therefore, a brief description of the materials and methods used in this chapter will be given below.

7.3.1 Design

This chapter presents findings from a repeated measure design and reports statistical comparison, and multivariate predictive analysis of foot function development between infants at two stages of walking (infants at onset of walking and confidently walking).

7.3.2 Participants

As for the previous chapter, only participants with pressure data set for the onset of walking (V2) and confident walking (V3), from both the University of Brighton and Salford, were used for this work. Infants were able to participate to data collection sessions if they were born full-term, without impairment in attaining walking stages or gross motor development deficiency. Infants were excluded if diagnosed, had history of or were referred to consultation for neurological or musculoskeletal conditions.

7.3.3 Testing procedure

Parents and infants were invited to the Universities of Brighton and Salford for testing at the attainment of two milestones, namely V2 (infants being able to take 3-5 independent steps) and V3 (infants taking 10-15 steps confidently and independently). Detailed description of the visits is reported in chapter 3. Participants had to attend each visit within 21 days since the first day of milestone attainment, or they were excluded from the analysis.

During each visit, plantar pressure data was collected using a Novel EMED xl platform (Novel, Munich, Germany), collecting at 100 Hz and with a sensor resolution of 4 sensors per cm^2. Videos were also recorded at each visit using a Vicon HD Camera (University of Brighton: Vicon Bonita 720c; Oxford, U.K/ University of Salford: Logitech HD Pro Webcam). The platform was placed in a nursery-style environment, and embedded in a soft mat, to ensure safety during testing (Figure 7). Infants were able to walk freely, to the extent of their abilities, at self-selected speed and in self-directed directions. The pressure system was triggered once infants initiated walking, for 60 seconds.

7.3.4 Data processing

Details of the pressure data processing framework are reported in chapter 4, section 4.3. Nevertheless, an additional phase of work has been undertaken, as pressure data from left and right feet in V2 and V3 were combined and analysed. Therefore, a brief description of the phases of work undertaken in this chapter will be reported hereafter.

7.3.4.1 Pressure data extraction

Steps were extracted from the walking trials of V2 and V3 using the 'define period tool' in the standard EMED software (Novel, Munich, Germany). Subsequently, each step within the selected frames was extracted singularly using the manual 'select free line tool' and saved.

7.3.4.2 pSPM data processing framework

Steps were excluded from processing if they were taken outside the platform borders and if they were missing extensive anatomical parts (Figure 12), as reported in chapter 4, section 4.3. Stance phases of each step were also checked to ensure processing of steps from full walking cycles. As for the previous chapters, only steps that originated from trials of straight-line walking were used for the analysis (chapter 3). Maximum pressure pictures (MPPs) of the steps were exported as ASCII text files (Novel Emascii software), and imported into Matlab 2019a (The Mathworks Inc, Natick, USA) as 2-dimensional (2D) numeric matrices for data processing and analysis. Each MPP was then positioned in a grid of 36x25 pixels, to standardise matrix dimensions of each MPP. Non-zero entries of the MPP matrices corresponded to pixels containing pressure values. The full data processing framework adopted in this chapter has been reported in figure 30, in the form of a flowchart.

1. Mirroring left and right maximum pressure pictures

MPPs of right feet were mirrored to the left feet (Willems et al., 2021), using a built-in Matlab function ("fliplr") that created new translated matrices to the left, which enabled further phases of data processing considering anatomical correspondences between feet.

2. Vertical rotation of the maximum pressure picture with principal component analysis

Once mirrored, each MPP was vertically aligned by performing a counter clockwise rotation to vertical using principal component analysis (PCA), which allowed definition of the principal axes of the foot (as eigenvectors), intersecting in the centroid of each MPP (Kim et al., 2013) (Figure 15). The angle Θ was then calculated using the longitudinal axis of the foot and the parallel to the y-axis in the Euclidean reference system of each MPP (Equation 4). Next, Θ was then applied to the rotation transformation matrix (Equation 5) that enabled rotation of each MPP to vertical (Figure 16).

3. Transformation of maximum pressure picture in point cloud

Once vertically rotated, MPPs were transformed into point clouds using a built-in Matlab function ("pointcloud") that transformed each pixel into a point, whilst pressure values within each pixel were stored in separate vectors.

4. Within-infant registration

After transformation was performed, within-infant registration was achieved using a rigid ICP algorithm (Besl and McKay, 1992). Next, for each vertex of the template a built-in Matlab function was used (based on Euclidean distances) that returns the nearest neighbours of a query point in the input point cloud ("findNearestNeighbours"), to find corresponding points between the single point clouds for each infant and the within-infant template.

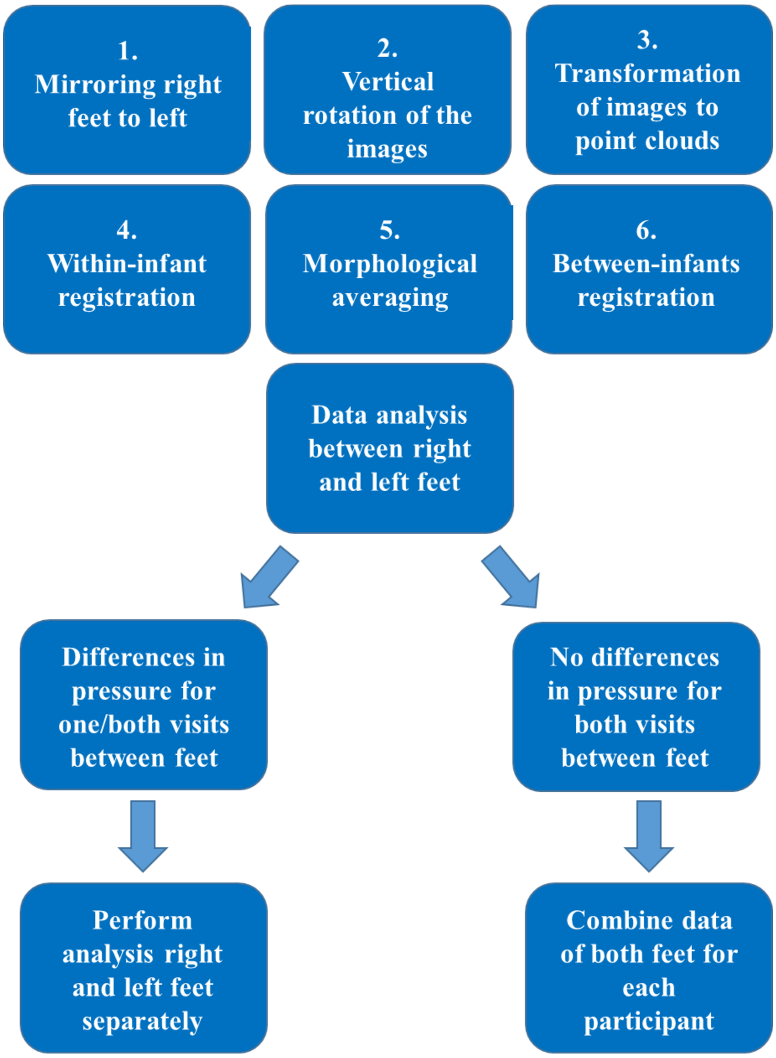
5. Morphological averaging

Once registered, corresponding coordinates of point clouds were averaged, resulting in one mean point cloud per participant per foot (Phethean et al., 2014).

6. Between-infants registration

To perform between-infants registration, a template was chosen as the point cloud with length and width closest to the mean length and width of all the within-infant mean point clouds (Pataky et al., 2011). Between-infant registration occurred between the template and the averaged sources using a non-rigid coherent point drift (CPD) algorithm. As after within-infant registration, for each vertex of the template a built-in Matlab function for point clouds was used based on Euclidean distances that returns the nearest neighbours of a query point in the input mean point clouds of each infant.

Figure 30. Flow chart reporting the main phases of the pSPM data processing framework used in this chapter.



7.3.5 Data analysis

Data was analysed in Matlab 2019a (The MathWorks, Natick, USA). As general requirement to proceed with the first analysis procedure, differences between left and right pressure data was checked (Appendix 3, Figure 42), due to the presence of different statistical outcomes highlighted in chapter 4, section 4.3. For this first phase of work, a two-tailed, nonparametric paired sample SPM1D t-test (http://www.spm1d.org/) was used, with significance set as $\alpha=0.05$, to check for differences in pressure between left and right feet in V2 and V3, separately. Comparison of left and right pressure images at each visit revealed the absence of significant differences (Appendix 3), and thus pressure data from left and right feet were combined for each participant, increasing the data sample. After differences in pressure between left and right feet were checked, the main plantar pressure inference was conducted between infants at the onset of walking and confidently walking using a two-tailed, nonparametric paired sample SPM1D t-test ($\alpha=0.05$). The statistical assumption related to the use of nonparametric inferences to analyse 2D pressure data have been reported in chapter 4, section 4.3.

Nonparametric linear regression was also performed at pixel level using SPM1D. Prior to linear regression, a correlation matrix was calculated in a custom-written Matlab script, based on Pearson product-moment correlation coefficients (r), to ensure that only items that were not moderate to strong correlated with each other ($r \geq 0.5$) were considered as independent variables within the broader analysis. This calculation was undertaken as indicators of growth such as height, weight and feet dimensions are likely related to each other as they increase as part of the overall body maturation. This is also why foot proportions (as the ratio between foot width and length, divided by 100) have been calculated in the regression model, to account for percent of growth of foot width with respect to foot length. Other independent variables considered initially in the regression model were body weight, height, foot length, foot width and walking experience (expressed as the total days infants took to be defined as new and confident walkers).

7.4 Results

In this chapter, 39 infants (20 females) were included in the analysis, as they had attended both V2 and V3. Demographic characteristics of the sample are reported in table 10.

Table 10. Sample demographics of Chapter 7.

	Onset of walking (V2)				**Confident walking (V3)**			
Measures	**Min**	**Mean**	**SD**	**Max**	**Min**	**Mean**	**SD**	**Max**
Age at visit (months)	9.1	13.3	1.6	16.6	12.3	15.6	1.8	20.2
Age at milestone (months)	8.6	12.8	1.5	16.2	11.8	15.1	1.8	19.6
Days since milestone (days)	7.0	14.5	5.1	21.0	3.0	15.2	5.5	21.0
Mass (kg)	8.0	10.3	1.3	13.8	8.5	11.0	1.3	14.0
Height (cm)	68.5	74.7	3.1	81.8	71.9	78.4	3.5	85.0
Foot length (cm)	9.7	11.4	0.7	12.6	10.5	11.9	0.8	13.6
Foot width (cm)	4.4	5.1	0.4	6.0	4.3	5.2	0.4	6.2
Foot proportion (%foot width/ foot length)	39.8	45.6	3.5	55.1	36.1	45.7	9.7	80.0

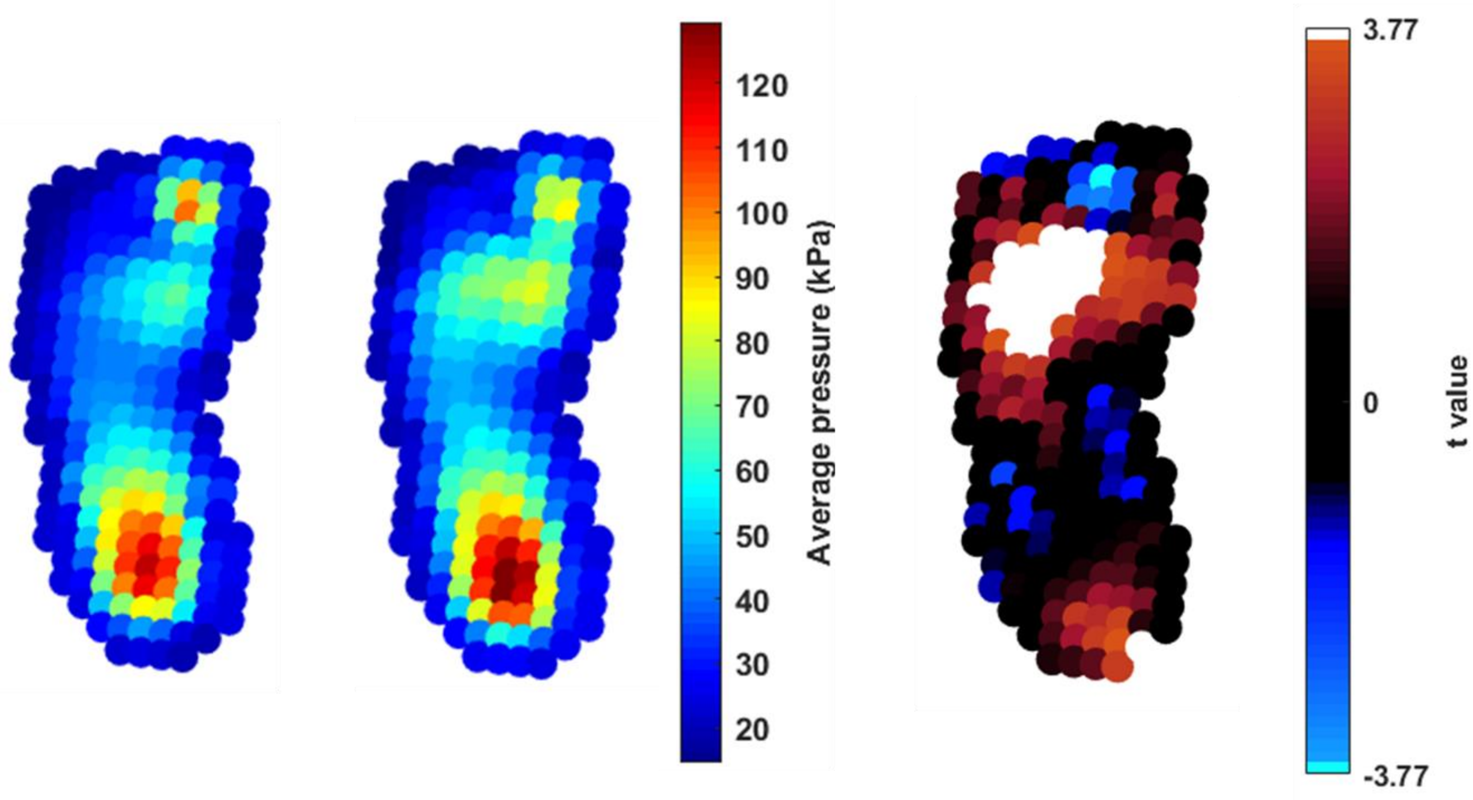
7.4.1 Pressure data overview

The absence of significant differences between left and right pressure data in each visit allowed statistical comparison to occur using a larger data sample, resulting in analysis of three steps for each foot, for each participant at each visit (3 steps *2 feet *39 participants *2 visits), for a total of 468 MPPs analysed.

7.4.2 Comparison of plantar pressures

Statistical comparison revealed the presence of significant changes in the transition to confident walking. Specifically, areas of significant increase in pressure were in the lateral to central forefoot (Figure 31). This was surrounded by a non-significant area of increasing pressure distributed across the forefoot, towards the lateral side of the midfoot, medial side of the hallux and lateral toes. A point of significant increasing pressure was also detected in the posterior medial border of the heel, surrounded by an area of non-significant increasing pressure that covered the posterior to central parts of the heel. In the medial and lateral sides of the midfoot, two areas of non-significant decreasing pressure once confident walking are evident. In the hallux, a point of significantly decreasing pressure was detected in the transition to confident walking, which was surrounded by points of non-significant reduced pressure.

Figure 31. Nonparametric pSPM paired t test for comparison between V2 and V3. From left to right: average pressure distribution of V2, average pressure distribution of V3, and raw t value of statistical analysis.



[12]

[12] The extremes of the colourbar in the inference image (extreme right) reflects t-values needed to reach statistical significance, with alpha set at 0.05. The colourbar for the average pressure distribution images presented different min and max kPa values that were adjusted by the overall max and min values to allow for comparison. Cool and warm colours identify where maximum pressure pictures (MPP) of confident walking infants had lower and higher peak pressure than new walkers, respectively.

7.4.3 Correlation matrix

The correlation matrix identified variables that significantly ($p<0.001$) and moderately correlated ($r \geq 0.5$) with each other (Figure 32). Specifically, there was a moderate positive correlation between height and age ($r=0.53$) and weight ($r=0.63$). A moderate positive correlation was also detected between body weight and foot length ($r=0.50$), whilst a moderate positive correlation was identified between walking experience and age ($r=0.59$) (Figure 32). When it came to decide which variables to consider in the regression model, the following considerations were made.

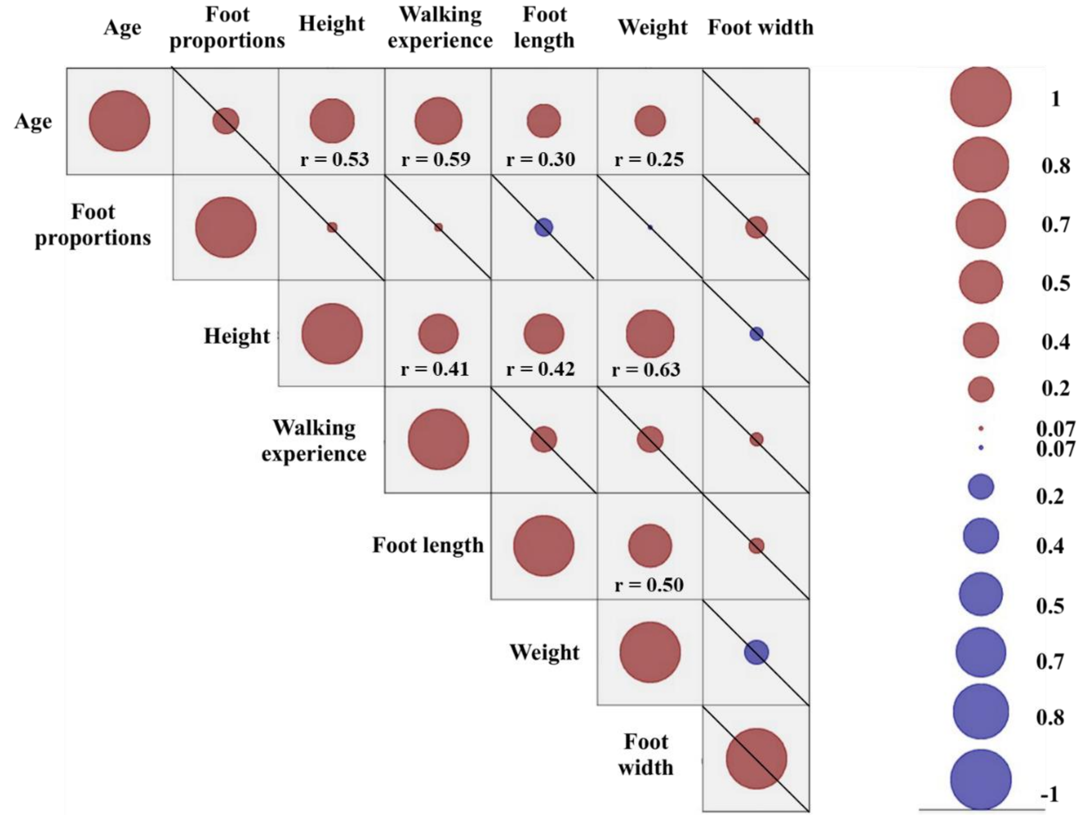
For example, walking experience moderately and significantly correlated with age only ($r=0.59$), whilst age also moderately correlated with height ($r=0.53$). Age would be generally considered more suitable to be used as predictor than walking experience, considering that it correlated with more items. However, the age of participants at each visit was not included as predictor for several reasons. First, it is important to identify that age represent only a chronological event and does not explain development (Adolph et al., 2012). In fact, infants in this thesis have been identified as new and confident walkers not based on a determined age but when they were able to accomplish several biomechanical requirements, e.g., taking 10-15 steps, navigating around objects, interact with parents and holding toys while walking. Using age to define the sample of the present work would likely fail to capture infants as new and confident walkers, as infants attain different stages of motor development at different age (Adolph et al., 2018). Furthermore, increasing age account for maturation of multiple body systems such as musculoskeletal, neurological, and does not represent a specific process of development. Therefore, developmental works using age in predictive model might fail to recognise specific predictors related to foot function changes, leading to generalised consideration.

In addition, this work also accounted for changes in foot sizes in 2D (changes in foot width relative to length) when including foot proportions within the regression model. This way, it was possible to separate findings related specifically to increasing foot length and width from the influence that the 2D changes in foot size might have had on plantar pressures. It is also recognised that other variables related to body maturation, such as tibial length or leg length, were not included in the model. In fact, it has been decided not to use these variables as they accounted partly for the overall increasing height, and thus the inclusion of height in the initial regression model was considered comprehensive of such changes. Height however was not included in the final regression model as two variables related to maturation were moderately correlated with weight, which was therefore included in the analysis as opposed to height.

Other variables that were not included in the model were the sex and the ethnicity of the participants. With respect to sex, it is important to cite the work from Unger and Rosenbaum (2004), who demonstrated that differences in sex produced different plantar pressures. To support that difference were due to sex and not to body weight variations, the authors also analysed a smaller group of infants from the broader sample observed and demonstrated that there were no differences in body weight between the analysed females and males. Nevertheless, comparing body weight of a sample size smaller than the one producing the main statistical results might be not representative of the real body weight differences present within the broader sample, as inter-individual variation in mass might be higher with analysis of larger amount of data. In addition, female, and male infants with the same body dimensions (weight, height, foot length etc.) might still produce different pressure patterns during walking that could likely not be due to the functional differences between sexes. Accordingly, stages of early walking development are a period when infants learn how to walk using different strategies (Bisi and Stagni, 2015).

In addition, the testing protocol adopted in this thesis for example, let infants walk freely and in any direction, leading to capture pressure data characterised by high inter-individual differences in foot shape, size, and orientation in the Euclidean space. Therefore, differences in pressure might be caused by the high inter-individual variability of contact pattern made as infants progressed forward (Price et al., 2017), which cannot be explained by sex differences. Furthermore, the literature does not report different characteristics of structural and morphological maturation of the feet between males and females in early stages of walking development, which have been investigated later in childhood and adolescence (Krauss et al., 2008, Tomassoni et al., 2014, Mickle et al., 2008). Therefore, separating males and females by using the differences in foot structure development would also not be possible, which further supports why sex was not included in the model. Apart from sex, also ethnicity has not been included in the regression model, as the sample analysed in this thesis did not demonstrate heterogeneous ethnical groups. In fact, the majority of the present sample was Caucasian, and did not demonstrate a variety of ethnicities that could have allowed an even stratification of the groups in terms of sample sizes.

Figure 32. Correlation matrix of the Pearson product-moment correlation coefficient (r) calculated among age, foot proportions, height, walking experience, foot length, weight, and foot width.



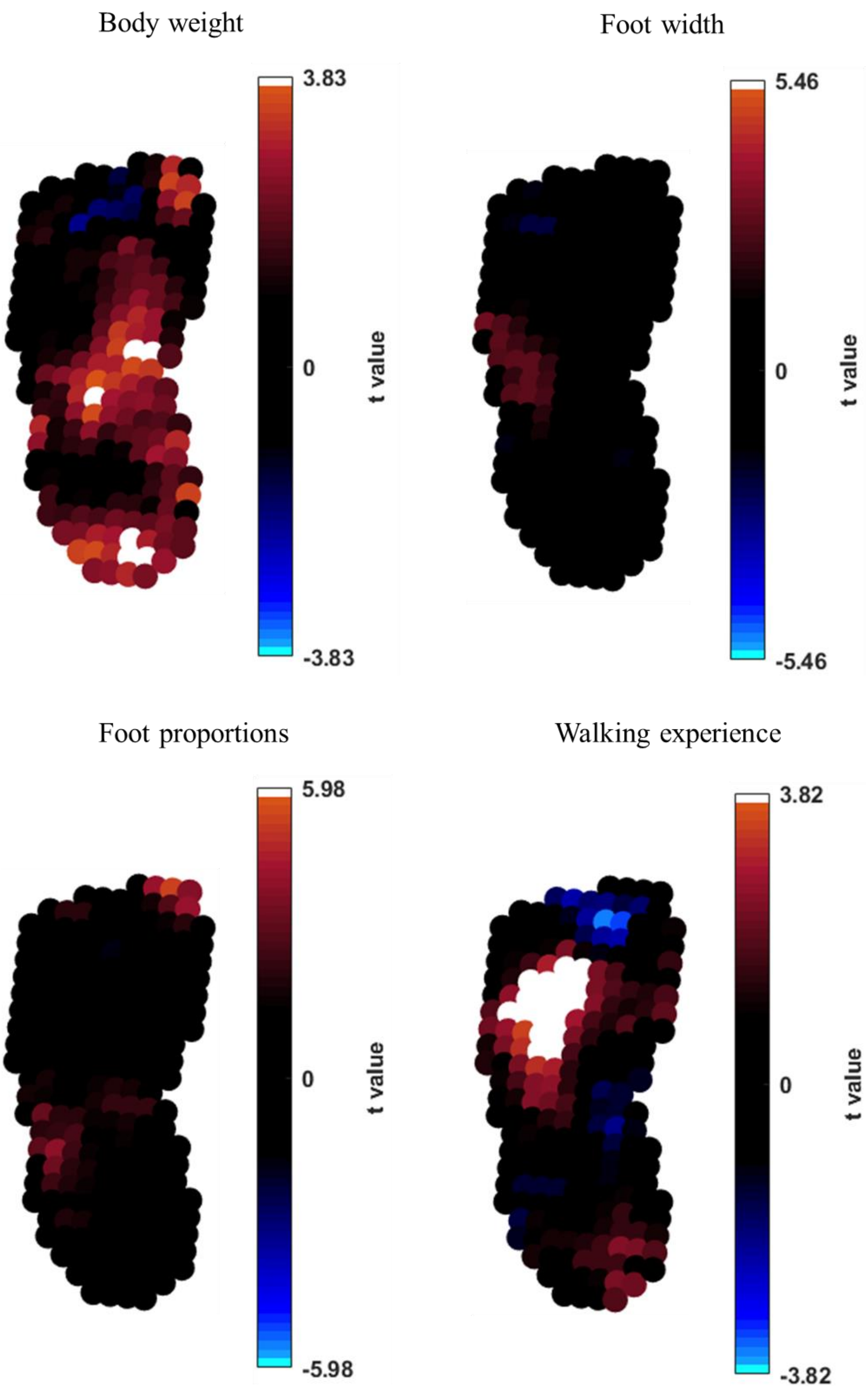
[13]

[13] The size of the circles indicates strength of the correlation (weak, moderate or strong), whilst the colour indicates the direction (positive or negative). Results that did not achieved significance were crossed and r were reported only for items that reached significant correlation (p=0.001).

7.4.4 Regression analysis

Regression analysis revealed significantly positive relationship between increasing body weight and pressure ($p < 0.05$; $t=+3.83$), which was detected in the medial midfoot, one point in the central midfoot and in the posterior border of the heel (Figure 33). Around these areas as well as in the hallux, there were positive yet not significant relationships between body weight and pressure (Figure 33). Additionally, the increasing walking experience also demonstrated a significant positive relationship with pressure ($p < 0.05$; $t=+3.82$), which was identified in the lateral and central forefoot. Non-significant relationship with walking experience and pressure were found also in the posterior border of the heel (positive relationship) and in the hallux (negative relationship). As opposed to body weight and walking experience, no relationships were demonstrated between foot width ($p \geq 0.05$; $t=\pm5.46$) and pressure, whilst areas of positive but not significant relationship between foot proportions and pressure were identified in the lateral midfoot and in the apex of the hallux ($p \geq 0.05$; $t=\pm5.98$) (Figure 33).

Figure 33. Nonparametric linear regression analysis at pixel level between body weight, foot width, foot proportions and walking experience and pressure.



[14]

[14] T-values indicates the strength of linear regression between increasing body weight and plantar pressure data. Extremes of the colourbar reflects t-values needed to reach statistical significance, with alpha set at 0.05.

7.5 Discussion

This chapter of the thesis aimed to offer a detailed account of plantar pressure changes from the onset of walking to confident walking stage, using continuous linear regression analysis to predict such changes across stages of walking development in infancy.

In contrast with the preliminary analysis reported in chapter 4 (section 4.3), the present results demonstrated the presence of several pressure changes occurring after 2.3 months of independent walking experience. One reason for this can be related to the increased sample size associated with analysis of a larger volume of pressure data in this work (N=468) compared to the preliminary work in this thesis (N=144), which might have contributed to highlight novel changes in pressure as infants became confident in walking. With respect to the wider available research in the field, this chapter showed the presence of significant plantar pressure changes that were not reported before (e.g., increasing pressure in the central forefoot and in the medial border of the heel). As already discussed in chapter 4 (section 4.3), this can be explained as previous observation adopted masking analysis using a reduced number of regions to analyse the plantar surface of the foot, preventing detection of changes in specific anatomical areas of the infants' feet. Whilst these methodological reflections have been discussed already in chapter 4, this work intended to build a discussion that enabled to demonstrate where and why pressure changes from the onset of walking to confident walking.

Accordingly, the analyses carried out in this work confirmed findings of chapter 4, section 4,3, demonstrating that plantar pressure distribution changes occur with increasing peaks in lateral and central forefoot. The presence of such changes was found to be predicted by the increasing walking experience. Specifically, increasing walking experience had a significant and positive relationship with increasing pressure in the lateral and central forefoot. The continuous experience obtained over time spent by walking has been described as a determinant factor to enable improvement of locomotion abilities (Adolph et al., 2012). Specifically, the authors reported that with accumulation of walking days, infants took more steps concurrently, travelled longer distances and demonstrated less falls (Adolph et al., 2012). With these results, it is therefore reasonable to surmise that biomechanical patterns of infants' gait also change. Accordingly, a study looking at 27 infants across the first year of life (observed from 1.6 to 18 months of age every four months approximately) measured harmony of walking calculating the ratios between durations of several spatiotemporal parameters (stance, swing and double support duration and stride length), comparing them with adult's golden ratio (De Bartolo et al., 2022). The authors demonstrated that infants from the onset of walking showed ratios of spatiotemporal parameters that started to be similar to the golden ratio of gait in adults, suggesting that through the increasing walking experience infants' gait' patterns improved. Therefore, walking experience can be considered as a determinant factor leading to improved walking abilities, and could be considered as an indicator of the overall gait development. The significant increasing pressure in the central forefoot has been attributed to the increasing walking speed in this sample by previous observation (Hennig and Rosenbaum, 1991), leading the interpretation of findings also in chapter 4, section 4.3. Accordingly, walking speed was showed to increase after five months from the onset of walking (Hallemans et al., 2005; Hallemans et al., 2006a). In an earlier study, Rosenbaum et al. (2013) found that when 8 years-old children were asked to increase their walking speed, plantar pressure patterns significantly increased across the metatarsal heads. The differences in the sample age between this chapter and the work from Rosenbaum et al. (2013) allow anticipating that children performed a more controlled and systematic faster gait than infants in this work, and this could lead to more accentuated changes in pressures. Nevertheless, it is reasonable to say that, as infants become confident walkers, walking speed increases consequently to gait improvement, which could lead to increasing pressure within the lateral and central forefoot. However, walking speed has not been measured in this work, and therefore, it would be necessary to use it in future predictive models, which would enable us to explain further the presence of changed plantar pressure patterns in the transition to confident walking.

With significant increasing pressure in the lateral and central forefoot, this work also demonstrated the presence of significant increasing pressure in the medial border of the heel. As only one point of pressure was significantly increasing from the onset of walking to confident walking, it would be reasonable to question the pixel resolution of the pSPM approach adopted in this chapter, as well as the relevance of such finding in the research and clinical context. With respect to pixel resolution, in section 4.3 of chapter 4, the errors due to pixels overlap were below 0.4 mm in both the registration algorithms, suggesting an accurate pixel resolution and thus a high level of confidence within the present results. With respect to the relevance of this result, one pixel of significant increasing pressure could not be considered determinant to quantify pressure distribution changes. However, the presence of such a restricted area of significance might be caused by the short gap between the two stages of walking. Because this is the first time that pSPM is adopted to compare infants at two stages of walking development, further studies should be carried out to check whether by increasing the gap between observations, larger areas of increasing pressure would be present. Nevertheless, it is important to notice that the increasing pressure in the medial heel is also in agreement with recent work from Price et al. (2022), who demonstrated that in the transition to confident walking, peak pressure in the medial heel significantly increased. It has to be highlighted that the large data set used in Price et al. (2022) (infants= 57) included in part some of the participants analysed in this chapter. Nevertheless, similarities in the results between these two works support the premises that adopting a high-resolution masking approach would yield results that are more precise and closer to continuous statistical inference. It can also be expected that by considering more data and participants, significant increasing pressure would be include more pixels within the medial heel.

The linear regression results of this work can help inform the presence of such changes. Accordingly, body weight showed a positive and significant relationship with increasing pressure in the heel, suggesting that as body weight increased, pressure increased in this area too. With this information, it is important to highlight that increasing initial contact with the heel has been demonstrated to occur after approximately two months of independent walking (Hallemans et al., 2003, Bertsch et al., 2004), which was also reported in chapter 6. Therefore, higher vertical loads generated by more weight were applied onto the heel at initial contact and can explain why pressure would increase in the transition to confident walking. It is reasonable to say that changes in heel pressure might be sensible to body weight variation also due to the contact area of the heel. Accordingly, the area covered by the heel is relatively small compared with other regions (e.g., the forefoot), and this has been reported in chapter 5. Thus, the increasing vertical loads at initial contact would be released onto a relatively small surface, which therefore causes pressure to rise (as P=F/A). If the same loads were applied onto a larger surface, pressure would possibly be lower.

In addition, the results of this chapter showed that as body weight increased, pressure in the central and medial midfoot also increased, reporting a significant positive relationship. Accordingly, also Bosch et al (2010) demonstrated that variations in typical weight could predict changes in foot morphology and function over nine years of observation. For example, the authors showed that with every increasing kg of body weight, there was a 3% increasing probability to detect higher peak pressures in the midfoot, which however was considered as a whole region. A positive yet not significant relationship between body weight and pressure was also demonstrated within the medial side of the foot. This might be explained by considering that the increasing body weight would be applied onto a structure characterised by laxity of soft tissues (Malina, 2003), a low medial arch profile (Bosch et al., 2010) as well as an everted posture of the ankle during walking (Samson et al., 2011). As a result, foot and ankle characteristics coupled with increasing weight would lead infants to intensify the loading demands onto the medial side of the foot during walking at these stages. Such considerations therefore highlight the importance to account for body weight changes in the field of infants' plantar pressure. This can be also supported by the choice of previous work to normalise pressure variables (e.g., maximum forces) were normalised to body weight, which enabled researchers to detect changes in pressure that were due to processes related with foot function development and not to increasing body size (Bertsch et al., 2004; Bosch et al., 2010).

Nevertheless, statistical comparison between infants at the onset of walking and confidently walking revealed that pressure in the media midfoot decreased, although not significantly. The reduced pressure at the midfoot was not reported before, and it can lead to interesting comparison with previous works. Accordingly, changes in peak pressure in the midfoot have not been clearly established by earlier observations (Bertsch et al., 2004; Bosch et al., 2010), which recorded a trend of both decreasing and increasing pressure throughout the observational periods. For example, Bertsch et al. (2004) reported that pressure in the midfoot increased from 73.1 to 78.0 kPa after three months of independent walking, which was then subject to a decrease at the 9th and 12th months of observation from the onset of walking. Using the same data set as Bertsch et al. (2004), Bosch et al. (2010) demonstrated that over nine years of investigation, pressure in the midfoot observed every three months approximately also showed a trend of increasing and decreasing values. The increasing pressure in the midfoot demonstrated after three months from the onset of walking (Bertsch et al., 2004; Bosch et al., 2010) might be due to identification of higher-loaded pixels in the lateral midfoot, for example, which have hidden patterns of reducing pressure in its medial counterpart. The decisions related to the use of the entire midfoot region in previous work was driven by considering the developing foot and its structural characteristics. In fact, the medial midfoot anatomically correspond to where the medial longitudinal arch (MLA) is in typically developed feet, as highlighted also in chapter 5. However, the infant foot is characterised by a low-medial arch profile as the MLA develops throughout infancy and childhood and becomes increasingly visible by the age of five years (Bosch et al., 2010). This arched structure is said to be used as a rigid lever enabling to transfer load from the heel to the forefoot efficiently (Venkadesan et al., 2020). The lack of a fully developed MLA structure might lead researchers to consider that differentiation in medial and lateral midfoot might not be necessary in infancy as functional midfoot changes would be expected once the MLA starts becoming more evident. However, this work as well as chapter 5 identified the presence of decreasing pressure in this area in the transition to confident walking, despite the developing structure and function of the MLA. This highlights that if masking analysis is adopted in paediatrics, the use of a higher number of regions to identify the midfoot areas (i.e., lateral, and medial midfoot) as changes in the medial midfoot start being present in early stages of gait development.

Areas of significant decreasing pressure were detected in the hallux. As for the heel, the presence of just one point of significant decreasing pressure might be debatable in terms of importance and relevance to inform changes in pressure distribution. However, the hallux in this sample is a considerably small anatomical area, (as reported also in chapter 5), which can be assumed not to activate many sensors during walking. Whilst this thesis adopted a high sensor resolution technology for plantar pressure data collection, the size of this anatomical site has to be considered as potentially limiting larger pressure areas to show significant results. Despite this consideration, it is interesting to notice that the present chapter highlighted a reduced pressure in the hallux with lower walking experience (2.3 months) in comparison with previous works. Accordingly, studies have reported significant decreasing pressure in the hallux to occur during the first three to six months of independent walking experience (Bertsch et al., 2004, Bosch et al., 2010). Sample demographics of these studies were similar to the one in the present chapter; however, a crucial difference between these studies and this chapter is present. In fact, previous works combined pressure data of trials where infants walked both independently and supported by parents. Assisting infants by holding them while walking has the potential to produce different biomechanical findings. For example, Ivanenko et al. (2005) found that when infants were supported by hand holding during walking, kinematics pattern changed, with reduction of as hips deviation, step width, percent of falls and trunk oscillations. As a result, it could be possible that infants walking partially supported could modify the amount of pressure applied in certain areas of the foot. This would lead to capture plantar pressure patterns at baseline observation that are not representative of the amount of pressure applied onto the foot during independent walking, with production of different statistical results over time. Despite these considerations, it is interesting to notice that the increasing foot proportions had a positive but not significant relationship with increasing pressure in the apex of the hallux, suggesting that changes of foot dimensions could positively predict changes in this area. Specifically, bones and soft tissues growth would cause changes of foot size that, without a concurrent change in shape, would determine an increased surface in contact with the ground. If force remained consistent, this would mean a reduction in pressure. However, the data reported in this work about foot proportions and foot width showed small to non-existent change from the onset of walking to confident walking, which might be due to the brief period passing between these two stages of walking. This might mean that changes in pressure could be predicted by increasing foot sizes occurring across more stages of walking development.

7.6 Limitations of the study

The methods adopted for analysis of plantar pressures enabled the identification of novel patterns of pressure changes across stages of walking in infancy, which were predicted by the increasing body dimensions as well as walking experience. However, it is important to note some challenges in the infants' measurement protocol. For example, this work addressed body maturation variables that were measured manually (by flexible tape) and by multiple researchers, in conditions where the infants might not always remain still. Moreover, this chapter lacked the presence of walking speed as predictor to plantar pressure changes, limiting understanding of its relationship with increasing pressure in certain areas of the foot such as the forefoot. Furthermore, walking experience was quantified based on the parent reporting when they believed infants met the inclusion criteria to be either new or confident walkers, which left some space for subjectivity. Finally, it has been anticipated that the brief period of observation between stages of walking might prevent pressure changes to be predicted by certain maturation variables such as foot width, which did not show changes from the onset of walking to confident walking. Extending the observation to other stages of walking in later infancy might capture more accentuated changes in foot size, which could have the potential to predict changes in plantar pressures.

In addition, it is recognised that in the field of predictive analysis, the use of multivariate predictive models has the potential to explain changes in the dependent variable while accounting for interactions among the predictors used in the model. Multivariate models such as general linear models in the SPM1d package exists but cannot be used in the field of continuous plantar pressure analysis. One of the reasons is that inference that consider multivariate analyses has been implemented only for parametric statistical tests in the SPM1d package. As explained in chapter 4, section 4.3, analysis of 2D pressure data with SPM is possible only if nonparametric inference is used, due to the underlying SPM assumption of 2D smoothness estimates and topological features estimates of the data (Pataky, 2010), which therefore needs future studies addressing this limitation.

7.7 Summary and conclusions

In this chapter, novel information related to changes in plantar pressures have been reported, using pSPM as a robust statistical approach for continuous analysis of plantar pressure data. Specifically, it has been demonstrated that several changes occurred as infants became confident walkers, such as:

- Increasing pressure in the lateral and central forefoot;
- Increasing pressure in the posterior medial border of the heel;
- Decreasing pressure in the hallux and medial midfoot;

This is the first time that changes in pressure in the medial midfoot, lateral forefoot and in the hallux have been reported to occur after 2.3 months from the onset of independent walking. Such novel characteristics related to foot function development have been reported to be due to differences between the present work and previous studies with respect to the testing protocol adopted (combination of trials originating from independent walking and hand holding walking) and methodological approaches adopted to investigate pressure changes in infancy (using discrete analysis as opposed to continuous). As a result, the present chapter highlighted the importance of selecting a methodology for pressure analysis that enable to identify changes in peak pressures without losing the spatial resolution of the data.

Furthermore, this is the first time that changes in plantar pressures were predicted by variables related to body maturation and by walking experience, which highlighted the interdependency of complex system to foot function changes in infancy. Specifically, two independent variables were identified as significant predictors of plantar pressure changes, namely:

- Walking experience:
- Body weight

Walking experience has been found particularity important to understand pressure changes in the forefoot, whereby the rapid accumulation of stepping experience acted to enhance improvement of gait patterns. This could have not been isolated by considering only age variations for example, as age represents a general sequence of events both related to body maturation and development and cannot be considered as an exploratory variable.

With the results related to prediction of plantar pressure changes using body weight, it has been highlighted that body weight has to be carefully considered in infants' plantar pressure studies, supporting the choice of previous works to normalise pressure values to body weight in order to mitigate its influence on plantar pressures. Whist it was not the intent of this chapter to discuss the musculoskeletal implications of atypical increase in body weight within the structure and function of the infant foot, these results anticipate the importance to monitor changes in body weight from infancy.

Foot width did not demonstrate any evident result, but foot proportion enabled detection of positive yet not significant relationship with pressure, suggesting that the overall increasing foot size could have the potential to predict changes in pressure in relation to increasing width (lateral midfoot) and length (apex of the hallux). Thus, future works should be undertaken with a larger sample and observing changes over a broader observational period, to allow foot dimensions to further increase.

Chapter 8. General discussion

Continuous and concurrent changes take place throughout infancy in several body systems, such as the neurological, sensory, and musculoskeletal system, which have the potential to underpin characteristics and development of foot function in the attainment of bipedal, upright locomotion. As a result, studying and quantifying foot function and its development would require a detailed biomechanical investigation, to account for the complex changes that take place in the transition to confident, independent walking.

The investigation of typical foot function development in infancy has received increasing attention (Hennig and Rosenbaum, 1991, Dulai et al., 2021). The literature review of this PhD highlighted that, despite the variety of pressure sensors and equipment to choose, plantar pressure technologies are relatively easy and intuitive to use for biomechanical exploration of the infant foot. The literature also demonstrated that masking analysis is the conventional and most commonly adopted approach to plantar pressure data reporting and interpretation, which however allow discrete statistical tests to be undertaken as opposed to continuous. As an alternative, the use of pSPM represent a continuous approach to plantar pressure analysis, which enables changes in pressure to be detected in the anatomical foot correspondence, avoiding loss of pressure information (Pataky and Goulermas, 2008). Its use was however limited to plantar pressure of adults (McClymont et al., 2016, Willems et al., 2021) and older children (Phethean et al., 2014), thereby lacking validation of its application to plantar pressure data in infancy.

Therefore, the available literature used mainly masking analysis approaches to explore plantar pressure data, collected at the earliest from the onset of independent walking (12 months of age approximately). Despite the increasing presence of literature in the field of infants' plantar pressure investigations, there were still some key limitations. Accordingly, studies have mainly investigated changes of regional plantar pressures to explore foot function development, such as modifications of peak pressures, contact times and contact areas, which have been extracted most commonly for five regions of interest including the heel, midfoot, forefoot and hallux. Such investigations also lacked a detailed exploration of plantar pressure patterns prior to walking stages and in nursery-style environments, using novel testing protocols to capture real-world pressure data across motor development (Price et al., 2018a). In addition, previous works did not include high-resolution approaches to plantar pressure analysis that treated the data in its meaningful spatial domain. Similarly, changes in pressure application over the plantar surface of the foot have also been reported through centre of pressure analysis (Bertsch et al., 2004; Hallemans et al., 2003; Hallemans et al., 2006b). However, the scarcity of studies related to centre of pressure data and the low-resolution approaches adopted in the available works limit knowledge of early foot-ground interactions changes in the transition to confident walking. In addition, the available research failed to quantify the relationship occurring between changes in pressure with variables of increasing body maturation (e.g., height, body weight, foot lengths etc.) and walking experience. As a result, there was the need to establish novel testing protocols and methodological approaches to capture real-world, objective patterns and changes of plantar pressures across motor development in infancy, which enabled the full description of typical functional characteristics and changes of the infants' weight bearing foot.

8.1 Methodological approaches to plantar pressures in infancy

In contrast with previous works, this thesis adopted a robust approach for plantar pressure data collection and treatment in infancy, which enabled participants to perform a series of motor activities as they would in their every-day environment, thereby being free to move in their preferred way and without being constrained in systematic motor directions (e.g., straight line walking). This approach was in agreement with research in the field of developmental psychology (Adolph et al., 2018, Adolph et al., 2003). However, it caused challenges with respect to biomechanical data processing and analysis, due to the highly variable foot placement onto the pressure platform (e.g., high intra and inter-individual variability of shapes, sizes, and orientation of the feet in the Euclidean space, as well as a high variability of plantar pressure values). Although these characteristics can be considered as typical of the sample observed in this thesis, they conflicted with the conventional analytical approaches to plantar pressure data processing and analysis, which have been implemented for typical plantar pressures and foot contact patterns.

The methodologies proposed to process, analyse, and interpret plantar pressure data in infancy have been demonstrated to be appropriate and accurate in chapter 4 of this thesis, and therefore suitable to characterise plantar pressure patterns and their changes as the infant foot developed from a newly weight bearing complex to a fully weight bearing structure. Specifically, both approaches used in chapter 4 relied on specific feet characteristics of the sample of interest for data processing, leading to several advantages.

For example, advantages of the customised mask used in this thesis were represented by the ease in processing a large amount of pressure data efficiently. This made it possible to describe precisely changes in pressure not only with respects of peaks but also considering other variables such as contact areas and times that enhanced data interpretation. The limitation of masking analysis has been extensively discussed and are related to statistical data treatment (discrete statistical treatment), resulting in a low-resolution approach for statistical analysis of infants' pressure data. Alternatively, the continuous statistical treatment with pSPM made such an approach more suitable to understand differences in plantar pressures between stages of walking development. In fact, this thesis has reported that when a small number of regions of interest is adopted (e.g., five regions), researchers might miss detection of important pressure patterns hence information related to foot function and its development in infancy. For example, using the whole forefoot or midfoot as opposed to consider precise anatomical regions (e.g., metatarsal heads) could lead to generalise pressure information instead of considering specific changes occurring within either the lateral forefoot or central forefoot. Selection of regions of interest as whole instead of considering dividing them in their medial and lateral components might be caused by the ongoing development of the musculoskeletal structures of the infants' feet, which prevent a consistent and precise anatomical identification of anatomical landmarks such as the metatarsal heads.

With pSPM, these limitations were overcome by identifying plantar pressure changes in the meaningful spatial domain of the developing feet in infancy, which again supported the importance to select a continuous statistical methodology as opposed to discrete. Given these considerations, biomechanical developmental studies might benefit more from statistical analyses undertaken with pSPM instead of masking analyses but could still consider adopting masking separately or in addition to pSPM, to enhance pressure data description, providing a comprehensive analysis of plantar pressures.

Despite the robustness and objectivity of pSPM, limitations are present, and are mainly related to its implementation as well as its reproducibility in other research and clinical settings. Accordingly, chapter 4 proposed a processing framework that was implemented on a relatively small data sample. Even in chapter 7, pSPM was implemented considering a limited amount of pressure images for each infant. Analysing a larger data set (as in chapter 5) might be too computationally demanding with the pSPM approach proposed in this thesis, as several time-consuming phases of data processing prior to analysis would be required. This also demonstrates the need of programming skills experience to be able to process data according to the pSPM requirements (e.g., registration of pressure images). Such limitation could be overcome by creating dedicated software for processing infants' pressure images, using the approach validated in this thesis. Alternatively, it could be possible to releasing the Matlab codes used in this work, which would make this processing framework available for the wider scientific community.

Another key point that has to be considered in relation to the pSPM implementation is its transferability to processing and analysis of pressure images originating from walking trials of atypical development (e.g., cerebral palsy). This is due to the capability of the described approach to deal with irregular pressure images and the lack of assumptions relating to foot function that would be required to apply a relevant regional mask. In fact, the pSPM approach proposed in this thesis was based specifically on the infants' pressure data collected, which means that researchers and clinicians would require spending time understanding the phases of work necessary to process the data they collect, according to the principles underpinning SPM. In other words, the pSPM approach used in this thesis is highly dependent upon the available data and it might or might not require the same data processing phases highlighted in this thesis. Because of these data-dependence characteristics, the level of processing accuracy that has been reported in chapter 4 cannot be totally anticipated to be present when pressure data collected with different testing protocols and from different samples. Finally, it has been anticipated in chapter 4, section 4.3 that to consider differences between pressure images in the anatomical correspondences of the infants' feet, steps that were made only with small part of the foot surface (e.g., the forefoot) were not included, and ensuring pixel-by-pixel correspondence among images. As a result, it is recognised that part of the information captured by steps made only with the heel or forefoot have been ignored, highlighting another limitation of pSPM in relation to infants' pressure data analysis.

Therefore, by considering the computational demands to use pSPM as well as the data-dependence of its processing framework, it is possible to understand why it has not been adopted for infants' pressure data analysis before, despite its high-resolution approaches to statistical data treatment. Future work should be undertaken adopting this approach for analysis of pressure data captured from other paediatric populations, as pSPM has the potential to increasingly enhance understanding of pressure data that could highlight novel characteristics of foot function development. Understanding its statistical principles and its use associated with infants' pressure data would also not only make this approach useful for 2-dimensional pressure data analysis, but also for analysis of variables related to pressure application, such as the centre of pressure. Accordingly, this work was able to investigate plantar pressure changes with SPM as infants performed a series of weight bearing motor activities through these methodologies. Findings from each chapter were therefore collated in the next paragraph, to provide a full account of foot function characteristics and development from the stage of pull to stand to confident walking.

8.2 Foot function characteristics of the infant weight bearing foot

The description of plantar pressures originating from the present data set enabled to report unique functional characteristics of the infant weight bearing foot prior to independent walking stages, which were not described by existing literature. Specifically, the foot started being loaded increasingly often as bipedal locomotion developed, and the infants accomplished the motor tasks according to the extent of their motor abilities. During trials of pull to stand, infants used their feet as dynamic, weight-bearing organs. Accordingly, analysis of pressure data at this stage demonstrated that the foot represented an additional provider of stability that enabled infants to pull themselves up to stand without help from parents. Its function contributes to aid the activity of the upper limbs, by providing an additional weight-bearing, supporting surface to use while pulling up to stand. As a result, the activity of the foot at this stage became essential to accomplish a new advantage position that allow infants to interact more actively with parents, reach for toys, exploring the surrounding environment and establishing the basis for the development of other locomotion strategies such as cruising.

Infants started to load the foot cyclically as walking became the preferred way of locomotion. Choosing to walk over other locomotion strategies, such as crawling, might be explained as infants become increasingly motivated to walk in the first place, because walking allows them to travel more distances, faster and enhance a better exploration of the surrounding environment (Adolph et al., 2012). As a result, the foot was used similarly between the onset of walking and confident walking, as it became the only surface in contact with the ground at these stages, thereby representing the primary biomechanical interface between the body and the environment. Its functional characteristic therefore changed from an aiding and stabiliser organ to a structure enabling infants to move around more efficiently and without external supports. Nevertheless, constraints related to progress forward whilst maintaining balance and coordination led to differences in foot function emerging between the two stages of walking. Specifically, chapter 5 demonstrated the presence of long stance times and high contact areas at the onset of walking. This could be explained as infants at the onset of walking lacked of stability and therefore were trying to ensure a larger base of support by spending more time with their feet in contact with the ground during gait, which would lead to a consequent increase in contact areas. This would help infants to mitigate the loss of balance, combining aspects of foot function in pull to stand with the more active characteristics of the foot in confident walkers.

Assumptions related to foot function similarities between trials of pull to stand and walking were possible considering the presence of plantar pressure patterns that seemed to perpetuate across milestones, such as the high involvement of the forefoot during stance, the greater pressure applied in the heel and the lower pressure in the medial midfoot compared to the lateral. Within the stage of pull to stand, previous work reported the presence of different stages of ability in performing this motor task, that were not considered in this thesis (Atun-Einy et al., 2012). Furthermore, it was also recognised that between the stage of pull to stand and the onset of walking, other motor milestones might have been performed, such as cruising, for which plantar pressure data were not described, and thus considerations of foot function similarities across the observed milestones have to be made with care. Despite these considerations, the aforementioned results enabled to consider the possibility that pressure patterns typically seen during walking might originate from pull to stand as a form of first bipedal upright locomotion development. Consequently, the typical plantar pressure patterns in confident walking might be the result of innate processes related to foot biomechanics that start being present once the foot is used as a dynamic weight-bearing organ. Such processes are then improved and integrated into sequences of more complex movement and adapted to the more demanding loading requirements necessary to progress forward efficiently.

In this context, it has been anticipated in chapter 2 (section 2.3.1) that the calcaneal bony composition was reported to allow greater loads being dissipated more efficiently throughout the plantar surface of the foot. This is why the heel has been supposed to be the causing a more plantigrade foot posture during development of bipedal gait in apes (Latimer and Lovejoy, 1989). As a result, the present thesis demonstrated that the function of the heel to bear greater and more cyclic loads is present from the first time the foot start being used as a dynamic weight-bearing organ, and not only during walking. This finding was not reported before and might support the presence of innate biomechanical patterns of foot loading as bipedal locomotion establishes, which cause the infant foot to load the heel with higher pressures, as this area is structured to support such loads and transmit them efficiently throughout the plantar surface. However, establishing a direct link of foot function changes from trials of pull to stand to confident walking was not possible quantitatively, as pressure data originating from trials of pull to stand could not be compared with trials of walking. Nevertheless, analysis of plantar pressure changes identified important and novel information related to foot function development during walking, which also could provide the basis for development of further analysis within the stage of pull to stand for future works.

8.3 Foot function development from the onset of walking to confident walking

As highlighted in the previous paragraph, the foot passed from an aiding and stabiliser organ in pull to stand to being the only biomechanical interface between infants and the external environment during establishment of walking. As typical foot functional characteristics emerged within each motor milestones, this thesis also demonstrated that several patterns of plantar pressures changed rapidly, after only 2.3 months from the onset of independent walking.

Development of foot function was represented by a series of changes in plantar pressures from the onset of walking to confident walking. Specifically, initial foot contact was made with the midfoot area at the onset of walking, with high inter-individual variation within this phase of stance at this stage. With more walking experience, pressure was applied within the medial heel at initial contact. Chapter 6 provided an extensive discussion related to the possible mechanisms underpinning loading changes at initial contact. In brief, modifications in ankle posture during gait (Hallemans et al., 2006a) coupled with improved activity of leg muscles (Teulier et al., 2012, Okamoto et al., 2003) were identified as the possible main developmental events behind establishment of new foot-ground interactions at this stage, leading infants to a more plantigrade initial foot contact.

The presence of initial heel contact in confident walkers is the same initial contact pattern demonstrated by adults during walking (Grundy et al., 1975). This is also in agreement with previous works (Bertsch et al., 2004; Hallemans et al., 2003) as well as chapter 5, whereby it has been reported that the heel fulfils its function to dissipate the initial loadings throughout the plantar surface of the foot during weight-bearing activities. Initial medial heel contact could also explain why pressure in this area significantly increased, as demonstrated in this thesis. However, regression analysis in chapter 7 showed that body weight was a significant predictor of increasing medial heel pressure. Therefore, it is possible to say that variations in body weight associated with changes of initial contact pattern were key factors to consider changes in pressure application across stance as well as the amount of pressure applied in this area.

After initial contact, development of foot function occurred with decreasing medial pressure application from 20 to 70% of the stance in confident walkers, as it was found to be closer to the longitudinal axis of the foot. This does not mean that infants at this stage demonstrated lateral pressure application in this period stance. In fact, the between-infants medio-lateral trajectory was not found laterally to the longitudinal axis of the foot throughout the entire stance. However, the centre of pressure trajectories were averaged among infants, thereby hiding patterns of lateral pressure application for some infants. Therefore, it is possible to state that confident walking infants explored a different loading pattern compared to new walkers from 20 to 70% of stance, which in some instances resulted in lateral pressure application, which is in agreement with adults' feet biomechanics (Pataky et al., 2014).

The reduced medial pressure application from 20-70% of stance in confident walking might support the presence of significant increasing pressure in the lateral and central forefoot. Understanding why pressure in the lateral and central forefoot changed was one of the challenges highlighted in chapter 7, as there are limited considerations that could be drawn only considering the spatial aspects of pressure changes. Apart from considerations that can be drawn by combining the different types of data, the only parameter that enabled predicting such changes was the increasing walking experience, which was positively and significantly associated with changes in pressure in these areas. Given that increasing walking experience can be considered as an indicator of the overall gait development, it has been reported that factors associated with increasing walking abilities, such as higher walking speed (Hallemans et al., 2005), could be possibly associated with higher pressure in these areas, which was also reported before (Hennig and Rosenbaum, 1991). This highlighted the importance of walking experience as exploratory variable to detect overall changes in gait, but supported, at the same time, the premises reported in chapter 7, whereby specific variables related to gait development should be accounted as predictors to plantar pressure changes.

The presence of a reduced medial pressure application with more confident walking could also underpin the decreasing pressure in the medial midfoot demonstrated in chapter 7. This was also appreciated in chapter 5, with persistent lower contact areas, peak pressures and contact times in this area compared to the lateral midfoot at the onset of walking and confident walking. The presence of decreasing pressures in the medial midfoot would support the discussion made in chapter 5 and 7, confirming that the medial midfoot is a functional unit that should involve masking it with a separate region of interest in future studies adopting discrete analysis approaches. Important considerations related to the medial midfoot were also made by considering the relationship of body weight with peak pressures in this area as well as in the medial side of the foot in general. Specifically, this is the first time that regression analysis identified the presence of significant positive relationship between increasing body weight and peak pressures in the medial midfoot, and a positive yet not significant relationship between body weight and pressure in the medial side of the foot in general. As a result, chapter 7 highlighted the implications of body weight variations in infancy, underpinning its importance related to the medial midfoot function.

The pattern of medio-lateral pressure application highlighted in chapter 6 also demonstrated that the stance phase at the onset of walking and confident walking terminated with a medial loading with respect to the longitudinal axis of the foot, supporting the presence of push off with the hallux. With this, it would have been plausible to expect, as for the other areas of the foot, an increasing pressure in the hallux from the onset of walking to confident walking, which however significantly reduced. A reduction in pressure within the hallux was also visible in chapter 5, with values passing from 99.6 kPa at the onset of walking to 96.8 kPa in confident walking in this area, which is also consistent with previous works (Bertsch et al., 2004; Bosch et al., 2010). Changes in initial contact pattern from the midfoot to the heel might cause a decreased involvement of the anterior areas of the foot during stance, as pressure started being distributed just from posterior to anterior areas of the foot as opposed to record larger forward-backward displacement, which might have involved extra hallux loading throughout the entire stance. Increasing pressure in the hallux has been demonstrated to occur after six months from the onset of walking, suggesting the presence of an improved and more powerful push off with the big toe as stance terminates (Bertsch et al., 2004).

In addition to the above findings, chapter 6 also demonstrated significantly reduced mean path lengths, which can be seen as the decreasing medio-lateral displacement of centre of pressure in the transition to confident walking. The laxity of the foot and ankle complex in infancy allow them to have larger degrees of freedom within the movements associated with walking, exploiting the presence of instability. Long medio-lateral path length can be the caused by the compensatory movement of the ankle in the frontal plane, to mitigate the lack of stability. As a result, reducing medio-lateral path length highlighted a more controlled and stable pressure application across the foot in stance was visible, as infants did not require actuating any strategy at the ankle to maintain a stable foot placement while progressing forward. With higher stability, postural control also increased, and this was demonstrated by the concurrent reduction of the medio-lateral velocity of the centre of pressure with more confident walking. This suggests that as foot placement became more stable, infants developed the ability to control centre of pressure displacement more efficiently. As a result, they developed the ability to anticipate and control internal perturbations caused by production of voluntary movements (walking), characteristic of the anticipatory postural adjustment mechanism discussed in section 2.1.1 of chapter 2) (Westcott and Burtner, 2004), therefore, developing novel foot-ground interactions.

Thus, it is possible to surmise that as infants became confident walkers, a cascade of complex changes took place in several body systems. The musculoskeletal system maturated with changes represented by improvement of ankle posture during walking, muscles activity and increasing body weight. In addition, the improved stability, postural control, and walking experience underpinned development of the overall gait. Consequently, infants used the new acquired patterns of improved locomotion to experiment novel foot-ground interactions, underpinning the presence of foot function development characterised by the rapid establishment of an immature yet typical rollover pattern of the foot, which was not quantified before by the existing literature.

8.4. Implications for the scientific community

This thesis explored a high volume of pressure data, capturing the complexity and variability of foot function characteristics and development in early stages of infancy. Acquisition of such information is important in the paediatric field, as it helps generating new knowledge to help researchers and clinicians understand the typical pattern of foot development in infancy. Specifically, the following sections will consider the implications in both research and clinical settings originating from exploration of the weight-bearing foot function characteristics and development across infancy.

8.4.1 Research implications

Several aspects of this thesis can be useful to the research community exploring foot biomechanics during development. Through an extensive literature review, this thesis summarised information related to strengths and limitations of the existing choices related to sample recruitment, testing protocols, and equipment to collect plantar pressure data in infancy. Therefore, it has been possible to develop experimental chapters based on the most up-to-date findings extrapolated from the available research.

As a summary, researchers intending to develop studies addressing foot function development in infancy should consider capturing pressure data from infants recruited by motor abilities rather than age, in a nursery-style environment and without limiting infants to determined walking paths (e.g., straight line walking). From a more technical point of view, the equipment for infants' plantar pressure data collection should be high in sensor resolution (e.g., with at least 4 sensors per cm^2), considering the small infants' feet, preferring capacitive sensors technologies as opposed to resistive and collecting at high frequency (e.g., 100 Hz). As a result, this PhD highlighted the best practice to deliver updated and high-quality works in the field of plantar pressure that would be able to provide objective and real-world information related to foot biomechanics in infancy.

With respect to the experimental chapters developed in the thesis, it is possible to state that the extensive methodological work undertaken in this PhD enabled the development of a novel, robust and high-resolution approach to infants' plantar pressure data processing and analysis. Through such work, this PhD provided solutions to the arbitrary methodological approaches selected up to date, delivering gold standard methodological procedures to investigate plantar pressures in infancy. Accordingly, the approaches developed in this thesis would enhance comparison and interpretation of findings originating from future work, and avoid missing important pressure information related to foot function development in infancy.

This PhD also generated robust data that can be used as baseline for further research. For example, future work could look at comparing plantar pressure data captured from typically and atypically developing infants, which has been poorly explored over the years and thus, highlight the need to progress research in this field. This would provide the best practice to analyse data sets originating from different infants' populations as well increase understanding of the biomechanics of the foot in relation to pathological situation that can be used to improve knowledge of typical and atypical foot development and to enhance clinical practice.

In addition, this thesis also highlighted key points that researchers have to consider in future studies reporting plantar pressure. In fact, combining different biomechanical data analysis approaches enables the quantification of the changes occurring in the musculoskeletal system (such as changes in muscle activity, ankle posture). As a result, researchers could use these information to develop models for biomechanical data analysis in infancy that account for analysis of multiple data sets (e.g., kinematics, EMG), which could evidence an even more comprehensive understanding of foot biomechanics and its development across infancy.

8.4.2 Clinical implications

Whilst the sample observed and analysed in this thesis was not clinical, the knowledge generated within this thesis can be used to inform every-day clinical practice. Specifically, section 2.3.5 of the literature review (chapter 2) showed that across infancy, different foot conditions might affect the paediatric population (e.g., clubfoot), which can cause modifications of typical foot can function characteristics and development. Such alterations were captured investigating the profile of the plantar surface of the feet (Jeans and Karol, 2010; Jeans et al., 2014), as it has been showed in section 2.3.5. Accordingly, Jeans and Karol (2010) investigated plantar pressures of two years-old infants after surgical interventions (Ponseti method) and physical rehabilitation for clubfoot, highlighting improved foot function in the treated population compared to the control group (which did not undertake any intervention). Later, Jeans et al. (2014) studied plantar pressures of 30 infants and children aged between two and six years who underwent surgical anterior tibialis tendon transfers for clubfoot condition. Such studies were important as plantar pressure assessment allowed researchers to identify changes in foot function towards a more even distribution of pressure across the plantar surface.

As a result, plantar pressure technologies can be used as a foot assessment tool in infancy by clinicians. In fact, foot health experts using plantar pressure platforms in their practice might find it valuable to capture plantar pressure information of patients affected by a foot condition, and compare the obtained information with the data presented in this thesis, which can be used as a data set representing typical foot function characteristics and development. This would help practitioners to appreciate whether the observe populations maintain typical foot function patterns or if those are altered, which would enhance clinical decisions related to intervention, rehabilitation, monitoring and so on. These information might be difficult to be captured with traditional musculoskeletal tools (foot posture index, pedograph), for several reasons.

First, traditional measures are taken when the patient is standing still, and do not provide an understanding as foot function patterns or how those are developing during dynamic tasks that infants or children perform every day, in their own environment. Another challenge when clinicians assess infants' feet is represent by the fact that infants do not tend to be still during standing examination, so that practitioners might find it difficult to perform a detailed investigation using traditional ways of musculoskeletal foot assessment. Second, using foot posture index, for example, might be of limited relevance in infant populations, as they present foot anatomical structures that are highly immature and anatomical landmarks are challenging to be identified. Therefore, measures of foot posture that are generally used in adults or older children such as foot posture index are not be externally valid and meaningful for the assessment of infants' feet. Another way to assess clinically patterns of foot function and its development during motor activities in infants might be using video analysis, which however is limited in relation to the amount of information that can be drawn from the specific foot-ground interactions, which would therefore be ignored. Therefore, using plantar pressure technologies can be considered more advantageous to assess infants' foot function and monitor intervention in clinical practice, as they allow infants to perform their every-day activities while collecting data that can provide a detailed foot function evaluation.

Accordingly, infants would just have to walk over the platform as they would in their home environment, which lead to a more successful as well as valid capture of information that does not constrain infants to examination of feet that are generally performed on adults or older children.

It is recognised that if practitioners do not routinely capture plantar pressure in their every-day settings, its relevance in clinical populations might be limited. Accordingly, it has to be considered that plantar pressure software and platforms are expensive equipment, and despite their easy and intuitive user interfaces, they might not be accessible to everyone. Therefore, the findings provided in this thesis generated new knowledge about infants' foot function development, identifying key changes that occur early and can be used to inform how practitioners interpret clinical findings and make decisions. As an example, this thesis identified a persistent medial pressure application across the entire stance phase in infants who started to walk and who were already confidently walking. It can be assumed that such functional pattern causes the flexible foot of infants to assume a pronated position while walking, which can alarm parents. Thus, when infants are presented at the attention of foot health practitioners, this pattern of foot function has to be interpreted as a typical sign of development. Similarly, infants who use their forefoot as a first contact interface when they learn how to walk independently can generate apprehensions in parents, who has to be informed by clinicians in this field that this is typical for this motor stage, and that it will change when infants learn how to walk independently and confidently. As a last example, this thesis also proved the importance to monitor typical body weight also in infancy, as it can have an impact on the typical foot function in early stages of walking development, and thus, it should be carefully monitored across early motor development.

The information above has been reported to suggest how the data of this work could be used by clinicians to inform their clinical practice. Therefore, foot health practitioners can use the information provided in this thesis to update the current knowledge related to how typical functional development of the foot occurs in infancy. In addition, this information can also be shared with general practitioners, for example, to improve infants' foot health care. Consequently, education across disciplines could be improved, making it easier to identify for general practitioners the best health care professions to refer to when concerns and/or foot health issues are reported by parents. Accordingly, section 2.3.5 of chapter 2 highlighted issues related to the scarcity of information that general practitioners have about the importance of foot health in paediatrics, which can lead them to ignore important referral pathways (e.g., foot health experts) as well as have an impact on the awareness parents have about their children's feet health. As a result, parents' awareness about how foot function develops in early motor stages could be improved if clinicians uses the most up-to-date knowledge to inform parents about what has to be expected from foot function characteristics and development in infancy. This would avoid parents to worry when foot function patterns that are considered atypical in older children are shown in infancy (e.g., initial forefoot contact, persistent medial loading), therefore improving services and care.

8.5 Limitations of the thesis

Despite the robustness, and novelty of this PhD, some limitations were present and have been highlighted within each experimental chapters of this thesis. However, three main limitations will be addressed hereafter.

1. Pandemic impact

The spread of Sars-Cov-2 pandemic in March 2020 and the consequent worldwide lockdown caused a significant participant loss at the University of Brighton. Specifically, a final number of 54 infants were predicted to take part in the project, but only 12 of them completed the data collection up to March 2020. Whilst the data set collected at the University of Brighton was used for validation of the methodological approaches presented in this work, an additional amount of 27 infants were gathered from the data set collected at the University of Salford, in order to reach a larger sample size for development of the experimental chapters. Inclusion of the predicted participants from Brighton would have led this thesis to gather information from 81 infants overall. The data collection and testing protocols adopted in Salford were the same in Brighton, as part of the wider Great Foundation program, and was selected as infants having completed pull to stand trials and meeting the steps selection criteria for being included in the pSPM data processing.

2. Power calculations and sample

The experimental chapters where statistical analysis has been undertaken (chapter 6 and 7) did not undertake power calculation, to establish the number of infants necessary to answer the research questions with an important level of confidence. Power calculation within the SPM package has been developed in 2021 (Robinson et al., 2021), and its implementation has been reported only for sample size calculation of biomechanical 1-dimensional waveforms in Python. As a result, there are currently no studies adopting it to sample size estimation related to 2-dimensional pressure data. Analysis of centre of pressure data could have been complemented with power analysis, as trajectories were 1-dimensional, but the code elaborated in Python was released recently and it also should have been rewritten according to Matlab documentation, which was out of the scope of this PhD. The lack of power calculation therefore limits appropriation of this data set as fully normative, also because the sample was too homogeneous in terms of ethnicity and distribution within the territory.

3. Data collection and data treatment

Limitations related with the data used in this thesis are related to the data collection and treatment. Firstly, data has not been collected based on the specific motor milestones that are present between the stage of pull to stand and the onset of walking have (e.g., cruising). Therefore, it is recognised that foot function might demonstrate other characteristics before establishment of walking, which would require further investigations. Secondly, this thesis reported analysis of pressure data only, which limits interpretation of the information gathered, mainly for the absence of analysis originating from combined biomechanical data sets (e.g., plantar pressure data analysis associated with kinematic or electromyography data). The combination of biomechanical data analyses has been ignored mainly due to the amount of work that would have been necessary to develop a processing pipeline for the inclusion of kinematic data analysis. With respect to spatiotemporal gait characteristics, some of this knowledge could have been obtained from plantar pressure data. However, the focus of the thesis was to provide boundaries of normality related to plantar pressure distribution patterns across stages of motor development. This involved inclusion of individual left and right pressure steps that were not necessarily consecutive but that were all usable data from the full walking trials captured at the visits, preventing to collect spatio-temporal gait information that are captured from consecutive steps (e.g., step width, step length).

Finally, the testing protocol adopted in this work allowed infants to walk freely and unrestricted to systematic gait protocols, however only steps made in straight lines were used in this work, ignoring information originating from steps made while turning, which potentially increases understanding related to foot function characteristics and development according to different walking tasks performed.

4. Analysis approach

Limitations related to the statistical approach to data analysis were present with respect to the relationship between body maturation and practice with plantar pressures in chapter 7. Accordingly, this is one of the first times that linear regression analysis is performed in infancy with factors related to body maturation and development to enhance understanding of foot function changes. Multivariate analysis exists in the SPM package, but its use is limited to normally distributed data and could not be adopted for 2-dimensional pressure analysis given the statistical assumption behind pSPM reported in chapter 4 and 7.

8.4 Conclusions and future directions

This PhD analysed one of the largest plantar pressure data sets collected in infancy up to date, providing with new insights into characteristics of foot function as well as its development in the transition to confident walking. Specifically, this thesis was able to adopt high-resolution methodological approaches for plantar pressure analysis, combining information originating from regional pressure data as well as centre of pressure and peak pressures analysed in their continuous spatial domain. In addition, this is the first time that multiple variables related with body maturation as well as walking experience were used to predict plantar pressure changes in infancy, thereby providing a further explanation as to why plantar pressures change in the transition to confident walking.

As a general conclusion, it is possible to say that investigations undertaken in this thesis enabled to demonstrate the presence of specific patterns of foot function development, alongside the establishment of the typical yet immature rollover pattern of the foot, which originates after 2.3 months from the onset of walking. As stated above, the characteristics and development of foot function across infancy were demonstrated to be driven by continuous interactions between several processes related to neuromuscular-skeletal growth and experience, which were challenging to be separated from each other. As a result, this project captured the biomechanical uniqueness of infants' feet development, which still requires attention and future works to improve the current knowledge and underpin clinical practices.

Specifically, the field of plantar pressure is increasingly modifying over the years, and approaches to pressure data analysis are continuously updated and improved. Although this thesis adopted the most recent methodological approaches developed for plantar pressure analysis, understanding the complexity of foot function development in infancy requires a model that can account for several biomechanics behaviour from different data exploration (e.g., kinematic, electromyography etc.). In addition, the field of plantar pressure analysis in infancy would benefit from approaches that consider spatial-temporal aspects of foot-ground interactions, which have been applied only for adults' pressure studies. Specifically, future works should consider applying spatial-temporal analysis of plantar pressure data (STAPP) in the infants' pressure field, to generate information that consider when and where plantar pressure changes occur in the anatomical foot correspondences. Whilst the computational demand of such analysis is clear, as researchers would have to process the individual frames of pressure composing each step, it is also believed that with the information provided in this thesis, some challenges related to data processing (e.g., registration approaches, vertical rotation of the images) would be more easy to overcome. Therefore, it is expected that future works would be able to improve the knowledge and information emerged from this PhD with novel approaches to 2-dimensional pressure data analysis, leading to a more detailed understanding of the weight bearing foot function characteristics in the attainment of specific milestones occurring between pull to stand and the onset of walking.

References

ADOLPH, K. E., COLE, W. G., KOMATI, M., GARCIAGUIRRE, J. S., BADALY, D., LINGEMAN, J. M., CHAN, G. L. & SOTSKY, R. B. 2012. How do you learn to walk? Thousands of steps and dozens of falls per day. *Psychological science,* 23**,** 1387-1394.

ADOLPH, K. E. & FRANCHAK, J. M. 2017. The development of motor behavior. *Wiley Interdisciplinary Reviews: Cognitive Science,* 8**,** e1430.

ADOLPH, K. E., HOCH, J. E. & COLE, W. G. 2018. Development (of walking): 15 suggestions. *Trends in Cognitive Sciences,* 22**,** 699-711.

ADOLPH, K. E., RACHWANI, J. & HOCH, J. E. 2016. Motor and physical development: Locomotion. *The Curated Reference Collection in Neuroscience and Biobehavioral Psychology.* Elsevier Science Ltd.

ADOLPH, K. E., VEREIJKEN, B. & SHROUT, P. E. 2003. What changes in infant walking and why. *Child development,* 74**,** 475-497.

AKINS, J. S., KEENAN, K. A., SELL, T. C., ABT, J. P. & LEPHART, S. M. 2012. Test–retest reliability and descriptive statistics of geometric measurements based on plantar pressure measurements in a healthy population during gait. *Gait & Posture,* 35**,** 167-169.

ALEXANDER, R., BOEHME, R. & CUPPS, B. 1993. *Normal development of functional motor skills: the first year of life,* Therapy Skill Builders Tucson.

ALVAREZ, C., DE VERA, M., CHHINA, H. & BLACK, A. 2008. Normative data for the dynamic pedobarographic profiles of children. *Gait Posture,* 28**,** 309-15.

ANDERSON, M., BLAIS, M. M. & GREEN, W. T. 1956. Lengths of the growing foot. *J Bone Joint Surg Am,* 38-A**,** 998-1000.

AQUEVEQUE, P., OSORIO, R., PASTENE, F., SAAVEDRA, F. & PINO, E. Capacitive sensors array for plantar pressure measurement insole fabricated with flexible PCB. 2018 40th Annual International Conference of the IEEE Engineering in Medicine and Biology Society (EMBC), 2018. IEEE, 4393-4396.

ASSAIANTE, C., WOOLLACOTT, M. & AMBLARD, B. 2000. Development of postural adjustment during gait initiation: kinematic and EMG analysis. *Journal of motor behavior,* 32**,** 211-226.

ATUN-EINY, O., BERGER, S. E. & SCHER, A. 2012. Pulling to stand: common trajectories and individual differences in development. *Developmental psychobiology,* 54**,** 187-198.

BADALY, D. & ADOLPH, K. E. 2008. Beyond the average: Walking infants take steps longer than their leg length. *Infant Behavior and Development,* 31**,** 554-558.

BERNHARDT, D. B. 1988. Prenatal and postnatal growth and development of the foot and ankle. *Physical therapy,* 68**,** 1831.

BERTSCH, C., UNGER, H., WINKELMANN, W. & ROSENBAUM, D. 2004. Evaluation of early walking patterns from plantar pressure distribution measurements. First year results of 42 children. *Gait & posture,* 19**,** 235-242.

BESL, P. J. & MCKAY, N. D. Method for registration of 3-D shapes. Sensor fusion IV: control paradigms and data structures, 1992. International Society for Optics and Photonics, 586-606.

BISI, M. & STAGNI, R. 2015. Evaluation of toddler different strategies during the first six-months of independent walking: a longitudinal study. *Gait & posture,* 41**,** 574-579.

BLY, L. & ARIZ, T. N. 1995. Motor skills acquisition in the first year, an illustrated guide to normal development. LWW.

BOOTH, B. G., KEIJSERS, N. L. W., SIJBERS, J. & HUYSMANS, T. 2018. STAPP: Spatiotemporal analysis of plantar pressure measurements using statistical parametric mapping. *Gait Posture,* 63**,** 268-275.

BOOTH, B. G., KEIJSERS, N. L. W., SIJBERS, J. & HUYSMANS, T. 2019. An assessment of the information lost when applying data reduction techniques to dynamic plantar pressure measurements. *J Biomech,* 87**,** 161-166.

BOSCH, K., GERSS, J. & ROSENBAUM, D. 2007. Preliminary normative values for foot loading parameters of the developing child. *Gait Posture,* 26**,** 238-47.

BOSCH, K., GERSS, J. & ROSENBAUM, D. 2010. Development of healthy children's feet--nine-year results of a longitudinal investigation of plantar loading patterns. *Gait Posture,* 32**,** 564-71.

BOSCH, K. & ROSENBAUM, D. 2010. Gait symmetry improves in childhood—a 4-year follow-up of foot loading data. *Gait & posture,* 32**,** 464-468.

BRANTHWAITE, H., CHOCKALINGAM, N. & GREENHALGH, A. 2013. The effect of shoe toe box shape and volume on forefoot interdigital and plantar pressures in healthy females. *Journal of foot and ankle research,* 6**,** 1-9.

BREELAND, G., SINKLER, M. A. & MENEZES, R. G. 2020. Embryology, bone ossification. *StatPearls [Internet]*.

BRIL, B. & BRENIÈRE, Y. 1993. Posture and independent locomotion in early childhood: learning to walk or learning dynamic postural control? *Advances in psychology.* Elsevier.

BURNETT, C. N. & JOHNSON, E. W. 1971. Development of gait in childhood: Part II. *Developmental Medicine & Child Neurology,* 13**,** 207-215.

BUSHNELL, E. W. & BOUDREAU, J. P. 1993. Motor development and the mind: The potential role of motor abilities as a determinant of aspects of perceptual development. *Child development,* 64**,** 1005-1021.

BUTTERWORTH, M. L. & MARCOUX, J. T. 2019. *The Pediatric Foot and Ankle: Diagnosis and Management*, Springer.

CARLSTEDT, C. A. 1989. Biomechanics of tendons and ligaments. *Basic biomechanics of the musculosketal system***,** 59-74.

CHANG, C.-L., KUBO, M., BUZZI, U. & ULRICH, B. 2006. Early changes in muscle activation patterns of toddlers during walking. *Infant Behavior and Development,* 29**,** 175-188.

CHEN, L.-C., METCALFE, J. S., JEKA, J. J. & CLARK, J. E. 2007. Two steps forward and one back: Learning to walk affects infants’ sitting posture. *Infant Behavior and Development,* 30**,** 16-25.

CHENG, J. C., LEUNG, S. S., LEUNG, A. K., GUO, X., SHER, A. & MAK, A. F. 1997. Change of foot size with weightbearing. A study of 2829 children 3 to 18 years of age. *Clinical orthopaedics and related research***,** 123-131.

CHESTER, V. L., TINGLEY, M. & BIDEN, E. N. 2006. A comparison of kinetic gait parameters for 3–13 year olds. *Clinical Biomechanics,* 21**,** 726-732.

CHEVALIER, T. L., HODGINS, H. & CHOCKALINGAM, N. 2010. Plantar pressure measurements using an in-shoe system and a pressure platform: A comparison. *Gait & posture,* 31**,** 397-399.

CLARK, J. E. & PHILLIPS, S. J. 1993. A longitudinal study of intralimb coordination in the first year of independent walking: a dynamical systems analysis. *Child development,* 64**,** 1143-1157.

CLARK, J. E., TRULY, T. L. & PHILLIPS, S. J. 1990. A dynamical systems approach to understanding the development of lower limb coordination in locomotion. *Sensory-motor organizations and development in infancy and early childhood.* Springer.

CORNWALL, M. W. & MCPOIL, T. G. 2000. Velocity of the center of pressure during walking. *Journal of the American Podiatric Medical Association,* 90**,** 334-338.

COUSINS, S. D., MORRISON, S. C. & DRECHSLER, W. I. 2012. The reliability of plantar pressure assessment during barefoot level walking in children aged 7-11 years. *Journal of foot and ankle research,* 5**,** 1-8.

COUSINS, S. D., MORRISON, S. C. & DRECHSLER, W. I. 2013. Foot loading patterns in normal weight, overweight and obese children aged 7 to 11 years. *Journal of foot and ankle research,* 6**,** 1-6.

DE BARTOLO, D., ZANDVOORT, C. S., GOUDRIAAN, M., KERKMAN, J. N., IOSA, M. & DOMINICI, N. 2022. The Role of Walking Experience in the Emergence of Gait Harmony in Typically Developing Toddlers. *Brain Sciences,* 12**,** 155.

DE COCK, A., VANRENTERGHEM, J., WILLEMS, T., WITVROUW, E. & DE CLERCQ, D. 2008. The trajectory of the centre of pressure during barefoot running as a potential measure for foot function. *Gait Posture,* 27**,** 669-75.

DELGADO-ABELLÁN, L., AGUADO, X., JIMÉNEZ-ORMEÑO, E., MECERREYES, L. & ALEGRE, L. M. 2014. Foot morphology in Spanish school children according to sex and age. *Ergonomics,* 57**,** 787-797.

DEMIRBÜKEN, İ., ÖZGÜL, B., TIMURTAŞ, E., YURDALAN, S. U., ÇEKIN, M. D. & POLAT, M. G. 2019. Gender and age impact on plantar pressure distribution in early adolescence. *Acta orthopaedica et traumatologica turcica,* 53**,** 215-220.

DESCHAMPS, K., BIRCH, I., MC INNES, J., DESLOOVERE, K. & MATRICALI, G. A. 2009. Inter- and intra-observer reliability of masking in plantar pressure measurement analysis. *Gait Posture,* 30**,** 379-82.

DOMINICI, N., IVANENKO, Y. P. & LACQUANITI, F. 2007. Control of foot trajectory in walking toddlers: adaptation to load changes. *Journal of neurophysiology,* 97**,** 2790-2801.

DOWLING, A. M., STEELE, J. R. & BAUR, L. A. 2004. What are the effects of obesity in children on plantar pressure distributions? *Int J Obes Relat Metab Disord,* 28**,** 1514-9.

DULAI, S., RAMADI, A., LEWICKE, J., WATKINS, B., PROWSE, M. & VETTE, A. H. 2021. Functional characterization of plantar pressure patterns in gait of typically developing children using dynamic pedobarography. *Gait & Posture,* 84**,** 267-272.

DUNN, W. 1999. Sensory profile: User's manual San Antonio. *TX: The Psychological Corporation*.

ELLIS, S. J., STOECKLEIN, H., YU, J. C., SYRKIN, G., HILLSTROM, H. & DELAND, J. T. 2011. The accuracy of an automasking algorithm in plantar pressure measurements. *HSS Journal®,* 7**,** 57-63.

ÈOZKAYA, N. & NORDIN, M. 1991. *Fundamentals of biomechanics: equilibrium, motion, and deformation*, Van Nostrand Reinhold.

EVANS, A. 2010. Paediatrics. The pocket podiatry guide. Churchill Livingstone Elsevier New York, NY.

EYRE, J., MILLER, S., CLOWRY, G., CONWAY, E. & WATTS, C. 2000. Functional corticospinal projections are established prenatally in the human foetus permitting involvement in the development of spinal motor centres. *Brain,* 123**,** 51-64.

FELDMAN, R. S. 2006. *Development across the life span*, Pearson Education New Zealand.

FINESTONE, A. S., PETROV, K., AGAR, G., HONIG, A., TAMIR, E. & MILGROM, C. 2012. Pattern of outsole shoe heel wear in infantry recruits. *Journal of foot and ankle research,* 5**,** 1-7.

FRISTON, K. J., FRITH, C., LIDDLE, P. & FRACKOWIAK, R. 1991. Comparing functional (PET) images: the assessment of significant change. *Journal of Cerebral Blood Flow & Metabolism,* 11**,** 690-699.

FRISTON, K. J., HOLMES, A. P., WORSLEY, K. J., POLINE, J. P., FRITH, C. D. & FRACKOWIAK, R. S. 1994. Statistical parametric maps in functional imaging: a general linear approach. *Human brain mapping,* 2**,** 189-210.

FRISTON, K. J., STEPHAN, K. E., LUND, T. E., MORCOM, A. & KIEBEL, S. 2005. Mixed-effects and fMRI studies. *Neuroimage,* 24**,** 244-252.

FRITZ, B. & MAUCH, M. 2013. Foot development in childhood and adolescence. *Handbook of Footwear Design and Manufacture.*

FROEHLE, A. W., NAHHAS, R. W., SHERWOOD, R. J. & DUREN, D. L. 2013. Age-related changes in spatiotemporal characteristics of gait accompany ongoing lower limb linear growth in late childhood and early adolescence. *Gait & posture,* 38**,** 14-19.

FROST, H. M. 1994. Wolff's Law and bone's structural adaptations to mechanical usage: an overview for clinicians. *The Angle Orthodontist,* 64**,** 175-188.

GALLOWAY, J. C. & THELEN, E. 2004. Feet first: object exploration in young infants. *Infant Behavior and Development,* 27**,** 107-112.

GALNA, B. & SPARROW, W. A. 2006. Learning to minimize energy costs and maximize mechanical work in a bimanual coordination task. *Journal of motor behavior,* 38**,** 411-422.

GANLEY, K. J. & POWERS, C. M. 2005. Gait kinematics and kinetics of 7-year-old children: a comparison to adults using age-specific anthropometric data. *Gait & Posture,* 21**,** 141-145.

GIACOMOZZI, C. 2010. Appropriateness of plantar pressure measurement devices: a comparative technical assessment. *Gait Posture,* 32**,** 141-4.

GIACOMOZZI, C. & STEBBINS, J. A. 2017. Anatomical masking of pressure footprints based on the Oxford Foot Model: validation and clinical relevance. *Gait Posture,* 53**,** 131-138.

GOEL, K. & WATT, G. 2002. Paediatric podiatry. *Neale's disorders of the foot: diagnosis and management. 6th ed. London: Churchill Livingstone***,** 81-110.

GOULD, N., MORELAND, M., TREVINO, S., ALVAREZ, R., FENWICK, J. & BACH, N. 1990. Foot growth in children age one to five years. *Foot Ankle,* 10**,** 211-3.

GROUP, W. M. G. R. S. & DE ONIS, M. 2006. WHO Motor Development Study: windows of achievement for six gross motor development milestones. *Acta paediatrica,* 95**,** 86-95.

GRUNDY, M., TOSH, P., MCLEISH, R. & SMIDT, L. 1975. An investigation of the centres of pressure under the foot while walking. *The Journal of bone and joint surgery. British volume,* 57**,** 98-103.

GURNEY, J. K., KERSTING, U. G. & ROSENBAUM, D. 2008. Between-day reliability of repeated plantar pressure distribution measurements in a normal population. *Gait Posture,* 27**,** 706-9.

HALLEMANS, A., D'AOÛT, K., DE CLERCQ, D. & AERTS, P. 2003. Pressure distribution patterns under the feet of new walkers: the first two months of independent walking. *Foot & ankle international,* 24**,** 444-453.

HALLEMANS, A., DE CLERCQ, D. & AERTS, P. 2006a. Changes in 3D joint dynamics during the first 5 months after the onset of independent walking: a longitudinal follow-up study. *Gait Posture,* 24**,** 270-9.

HALLEMANS, A., DE CLERCQ, D., OTTEN, B. & AERTS, P. 2005. 3D joint dynamics of walking in toddlers A cross-sectional study spanning the first rapid development phase of walking. *Gait Posture,* 22**,** 107-18.

HALLEMANS, A., DE CLERCQ, D., VAN DONGEN, S. & AERTS, P. 2006b. Changes in foot-function parameters during the first 5 months after the onset of independent walking: a longitudinal follow-up study. *Gait & posture,* 23**,** 142-148.

HARBOURNE, R. T. & STERGIOU, N. 2003. Nonlinear analysis of the development of sitting postural control. *Developmental Psychobiology: The Journal of the International Society for Developmental Psychobiology,* 42**,** 368-377.

HART, E. S., GROTTKAU, B. E., REBELLO, G. N. & ALBRIGHT, M. B. 2005. The Newborn Foot: Diagnosis and Management of Common Conditions. *Orthopaedic Nursing,* 24**,** 313-321.

HAYAFUNE, N., HAYAFUNE, Y. & JACOB, H. 1999. Pressure and force distribution characteristics under the normal foot during the push-off phase in gait. *The foot,* 9**,** 88-92.

HENNIG, E. M. & ROSENBAUM, D. 1991. Pressure distribution patterns under the feet of children in comparison with adults. *Foot & ankle,* 11**,** 306-311.

HENNIG, E. M., STAATS, A. & ROSENBAUM, D. 1994. Plantar pressure distribution patterns of young school children in comparison to adults. *Foot & ankle international,* 15**,** 35-40.

HODGSON, L., HODGES, M., WILLIAMS, A. E., NESTER, C. J. & MORRISON, S. C. 2021. The “price-tag” of foot health in infancy and early childhood: a cross sectional survey of UK parents. *European Journal of Pediatrics,* 180**,** 1561-1570.

HODGSON, L., WILLIAMS, A. E., NESTER, C. J. & MORRISON, S. C. 2020. Steps towards evidence-based foot-care for children: Behaviour and opinions of health professionals. *Health & Social Care in the Community,* 28**,** 1651-1657.

HOLMES, G. L., MILH, M. M. & DULAC, O. 2012. Maturation of the human brain and epilepsy. *Handbook of clinical neurology,* 107**,** 135-143.

HUBBARD, A. M., MEYER, J. S., DAVIDSON, R., MAHBOUBI, S. & HARTY, M. 1993. Relationship between the ossification center and cartilaginous anlage in the normal hindfoot in children: study with MR imaging. *AJR. American journal of roentgenology,* 161**,** 849-853.

HUELKE, D. F. An overview of anatomical considerations of infants and children in the adult world of automobile safety design. Annual Proceedings/Association for the Advancement of Automotive Medicine, 1998. Association for the Advancement of Automotive Medicine, 93.

HUGHES, J., PRATT, L., LINGE, K., CLARK, P. & KLENERMAN, L. 1991. Reliability of pressure measurements: the EM ED F system. *Clinical Biomechanics,* 6**,** 14-18.

IVANENKO, Y. & GURFINKEL, V. S. 2018. Human postural control. *Frontiers in neuroscience,* 12**,** 171.

IVANENKO, Y. P., DOMINICI, N., CAPPELLINI, G. & LACQUANITI, F. 2005. Kinematics in newly walking toddlers does not depend upon postural stability. *Journal of neurophysiology,* 94**,** 754-763.

IVANENKO, Y. P., POPPELE, R. E. & LACQUANITI, F. 2006. Spinal cord maps of spatiotemporal alpha-motoneuron activation in humans walking at different speeds. *Journal of neurophysiology,* 95**,** 602-618.

JEANS, K. A. & KAROL, L. A. 2010. Plantar pressures following Ponseti and French physiotherapy methods for clubfoot. *Journal of Pediatric Orthopaedics,* 30**,** 82-89.

JEANS, K. A., TULCHIN-FRANCIS, K., CRAWFORD, L. & KAROL, L. A. 2014. Plantar Pressures Following Anterior Tibialis Tendon Transfers in Children With Clubfoot. *Journal of Pediatric Orthopaedics,* 34**,** 552-558.

JIMENEZ-ORMENO, E., AGUADO, X., DELGADO-ABELLAN, L., MECERREYES, L. & ALEGRE, L. M. 2013. Foot morphology in normal-weight, overweight, and obese schoolchildren. *European Journal of Pediatrics,* 172**,** 645-652.

KAIL, R. V. 2001. *Children and their development*, Prentice-Hall, Inc.

KELIKIAN, A. S. & SARRAFIAN, S. K. 2011. *Sarrafian's anatomy of the foot and ankle: descriptive, topographic, functional*, Lippincott Williams & Wilkins.

KELLIS, E. 2001. Plantar pressure distribution during barefoot standing, walking and landing in preschool boys. *Gait & posture,* 14**,** 92-97.

KERSHAW, E. E. & FLIER, J. S. 2004. Adipose tissue as an endocrine organ. *The Journal of Clinical Endocrinology & Metabolism,* 89**,** 2548-2556.

KIM, C., SON, H. & KIM, C. 2013. Fully automated registration of 3D data to a 3D CAD model for project progress monitoring. *Automation in Construction,* 35**,** 587-594.

KIRBY, K. & GREEN, D. 1992. Evaluation and Non-Operative Management of Pes Valgus Deformity. *In book: Foot and Ankle Disorders in Children.* Churchill-Livingstone.

KOUCHI, M. 1998. Foot Dimensions and Foot Shape: Differences Due to Growth, Generation and Ethnic Origin. *Anthropological Science,* 106**,** 161-188.

KRAUSS, I., GRAU, S., MAUCH, M., MAIWALD, C. & HORSTMANN, T. 2008. Sex-related differences in foot shape. *Ergonomics,* 51**,** 1693-709.

KRETCH, K. S., FRANCHAK, J. M. & ADOLPH, K. E. 2014. Crawling and walking infants see the world differently. *Child development,* 85**,** 1503-1518.

KRISTJANSSON, E. & TRELEAVEN, J. 2009. Sensorimotor function and dizziness in neck pain: implications for assessment and management. *journal of orthopaedic & sports physical therapy,* 39**,** 364-377.

LATIMER, B. & LOVEJOY, C. O. 1989. The calcaneus of Australopithecus afarensis and its implications for the evolution of bipedality. *American Journal of Physical Anthropology,* 78**,** 369-386.

LEDEBT, A., VAN WIERINGEN, P. C. & SAVELSBERGH, G. J. 2004. Functional significance of foot rotation asymmetry in early walking. *Infant Behavior and Development,* 27**,** 163-172.

LEHMAN, W. B. 2010. Drennan’s The Child’s Foot and Ankle. *JAMA*, 304**,** 1617-1618.

LOOK, N., AUTRUONG, P., PAN, Z., CHANG, F. M. & CAROLLO, J. J. 2021. Radiographic and plantar pressure assessment of pes planovalgus severity in children with cerebral palsy. *Clinical Biomechanics,* 85**,** 105364.

LOOPER, J. & CHANDLER, L. S. 2013. How do toddlers increase their gait velocity? *Gait & posture,* 37**,** 631-633.

LUNG, C.-W., HSIAO-WECKSLER, E. T., BURNS, S., LIN, F. & JAN, Y.-K. 2016. Quantifying dynamic changes in plantar pressure gradient in diabetics with peripheral neuropathy. *Frontiers in bioengineering and biotechnology,* 4**,** 54.

MAIER, E. & KILLMANN, M. 2003. *Kinderfuß und Kinderschuh: Entwicklung der kindlichen Beine und Füße und ihre Anforderungen an fußgerechte Schuhe*, Verlag Neuer Merkur GmbH.

MAKADIA, A., PATTERSON, A. & DANIILIDIS, K. Fully automatic registration of 3D point clouds. 2006 IEEE Computer Society Conference on Computer Vision and Pattern Recognition (CVPR'06), 2006. IEEE, 1297-1304.

MARTIN, J. H. 2005. The corticospinal system: from development to motor control. *The Neuroscientist,* 11**,** 161-173.

MATTHEWS, J. 1998. The developmental anatomy of the foot. *The Foot,* 8**,** 17-25.

MAUCH, M., GRAU, S., KRAUSS, I., MAIWALD, C. & HORSTMANN, T. 2008. Foot morphology of normal, underweight and overweight children. *Int J Obes (Lond),* 32**,** 1068-75.

MCCARTHY, J. J. & DRENNAN, J. C. 2009. *Drennan's the Child's Foot and Ankle*, Lippincott Williams & Wilkins.

MCCLYMONT, J., PATAKY, T. C., CROMPTON, R. H., SAVAGE, R. & BATES, K. T. 2016. The nature of functional variability in plantar pressure during a range of controlled walking speeds. *Royal Society open science,* 3**,** 160369.

MCCOLLUM, G., HOLROYD, C. & CASTELFRANCO, A. M. 1995. Forms of early walking. *Journal of Theoretical Biology,* 176**,** 373-390.

MCMILLAN, A. G. & SCHOLZ, J. P. 2000. Early development of coordination for the sit-to-stand task. *Human movement science,* 19**,** 21-57.

MERCER, J. 1998. *Infant development: A multidisciplinary introduction*, Wadsworth Publishing Company.

MERKER, J., HARTMANN, M., HAAS, J.-P. & SCHWIRTZ, A. 2018. Combined three-dimensional gait and plantar pressure analyses detecting significant functional deficits in children with juvenile idiopathic arthritis. *Gait & posture,* 66**,** 247-254.

MESQUITA, P. R., NERI, S. G. R., LIMA, R. M., MANFIO, E. F. & DE DAVID, A. C. 2019. Running and Walking Foot Loading in Children Aged 4-10 Years. *J Appl Biomech,* 35**,** 241-246.

METCALFE, J., CHANG, T. Y., CHEN, L. C., MCDOWELL, K., JEKA, J. & CLARK, J. 2005. Development of somatosensory-motor integration: An event-related analysis of infant posture in the first year of independent walking. *Developmental Psychobiology: The Journal of the International Society for Developmental Psychobiology,* 46**,** 19-35.

MICKLE, K. J., STEELE, J. R. & MUNRO, B. J. 2006. The feet of overweight and obese young children: are they flat or fat? *Obesity,* 14**,** 1949-1953.

MICKLE, K. J., STEELE, J. R. & MUNRO, B. J. 2008. Is the foot structure of preschool children moderated by gender? *Journal of Pediatric Orthopaedics,* 28**,** 593-596.

MOORE, K. L. & DALLEY, A. F. 1999. Anatomy. Clinically oriented. Baltimore: Lippincott Williams and Wilkins.

MÜLLER, J., MÜLLER, S., BAUR, H. & MAYER, F. 2013. Intra-individual gait speed variability in healthy children aged 1–15 years. *Gait & Posture,* 38**,** 631-636.

MULLER, S., CARLSOHN, A., MULLER, J., BAUR, H. & MAYER, F. 2012a. Static and dynamic foot characteristics in children aged 1-13 years: a cross-sectional study. *Gait Posture,* 35**,** 389-94.

MULLER, S., CARLSOHN, A., MULLER, J., BAUR, H. & MAYER, F. 2012b. Static and dynamic foot characteristics in children aged 1-13 years: A cross-sectional study. *Gait & Posture,* 35**,** 389-394.

MÜLLER, S., CARLSOHN, A., MÜLLER, J., BAUR, H. & MAYER, F. 2012. Static and dynamic foot characteristics in children aged 1–13 years: a cross-sectional study. *Gait & posture,* 35**,** 389-394.

OGUNLEYE, L., OYEJOLA, B. & OBISESAN, K. 2018. Comparison of some common tests for normality. *Int. J. Probab. Stat,* 7**,** 130-137.

OKAMOTO, T., OKAMOTO, K. & ANDREW, P. D. 2001. Electromyographic study of newborn stepping in neonates and young infants. *Electromyography and clinical neurophysiology,* 41**,** 289-296.

OKAMOTO, T., OKAMOTO, K. & ANDREW, P. D. 2003. Electromyographic developmental changes in one individual from newborn stepping to mature walking. *Gait & posture,* 17**,** 18-27.

OLIVEIRA, F. P., PATAKY, T. C. & TAVARES, J. M. R. 2010. Registration of pedobarographic image data in the frequency domain. *Computer methods in biomechanics and biomedical engineering,* 13**,** 731-740.

PALEY, D., BHAVE, A., HERZENBERG, J. E. & BOWEN, J. R. 2000. Multiplier method for predicting limb-length discrepancy. *JBJS,* 82**,** 1432.

PARK, K. B., PARK, H. W., LEE, K. S., JOO, S. Y. & KIM, H. W. 2008. Changes in Dynamic Foot Pressure After Surgical Treatment of Valgus Deformity of the Hindfoot in Cerebral Palsy. *JBJS,* 90**,** 1712-1721.

PATAKY, T. C. 2010. Generalized n-dimensional biomechanical field analysis using statistical parametric mapping. *Journal of biomechanics,* 43**,** 1976-1982.

PATAKY, T. C. 2012. Spatial resolution in plantar pressure measurement revisited. *Journal of biomechanics,* 45**,** 2116-2124.

PATAKY, T. C. 2016. RFT1D: Smooth one-dimensional random field upcrossing probabilities in Python. *Journal of Statistical Software,* 71**,** 1-22.

PATAKY, T. C., BOSCH, K., MU, T., KEIJSERS, N. L., SEGERS, V., ROSENBAUM, D. & GOULERMAS, J. Y. 2011. An anatomically unbiased foot template for inter-subject plantar pressure evaluation. *Gait Posture,* 33**,** 418-22.

PATAKY, T. C., CARAVAGGI, P., SAVAGE, R. & CROMPTON, R. H. 2008a. Regional peak plantar pressures are highly sensitive to region boundary definitions. *Journal of Biomechanics,* 41**,** 2772-2775.

PATAKY, T. C., CARAVAGGI, P., SAVAGE, R., PARKER, D., GOULERMAS, J. Y., SELLERS, W. I. & CROMPTON, R. H. 2008b. New insights into the plantar pressure correlates of walking speed using pedobarographic statistical parametric mapping (pSPM). *Journal of biomechanics,* 41**,** 1987-1994.

PATAKY, T. C. & GOULERMAS, J. Y. 2008. Pedobarographic statistical parametric mapping (pSPM): a pixel-level approach to foot pressure image analysis. *Journal of biomechanics,* 41**,** 2136-2143.

PATAKY, T. C. & MAIWALD, C. 2011. Spatiotemporal volumetric analysis of dynamic plantar pressure data. *Medicine and science in sports and exercise,* 43**,** 1582-1589.

PATAKY, T. C., ROBINSON, M. A., VANRENTERGHEM, J., SAVAGE, R., BATES, K. T. & CROMPTON, R. H. 2014. Vector field statistics for objective center-of-pressure trajectory analysis during gait, with evidence of scalar sensitivity to small coordinate system rotations. *Gait & Posture,* 40**,** 255-258.

PERRY, J. & DAVIDS, J. R. 1992. Gait analysis: normal and pathological function. *Journal of Pediatric Orthopaedics,* 12**,** 815.

PFEIFFER, M., KOTZ, R., LEDL, T., HAUSER, G. & SLUGA, M. 2006. Prevalence of flat foot in preschool-aged children. *Pediatrics,* 118**,** 634-639.

PHETHEAN, J. & NESTER, C. 2012. The influence of body weight, body mass index and gender on plantar pressures: results of a cross-sectional study of healthy children's feet. *Gait Posture,* 36**,** 287-90.

PHETHEAN, J., PATAKY, T. C., NESTER, C. J. & FINDLOW, A. H. 2014. A cross-sectional study of age-related changes in plantar pressure distribution between 4 and 7 years: a comparison of regional and pixel-level analyses. *Gait Posture,* 39**,** 154-60.

PIEK, J. P. 2002. The role of variability in early motor development. *Infant Behavior and Development,* 25**,** 452-465.

PIEK, J. P., DAWSON, L., SMITH, L. M. & GASSON, N. 2008. The role of early fine and gross motor development on later motor and cognitive ability. *Human movement science,* 27**,** 668-681.

PLOMIN, R. & ASBURY, K. 2005. Nature and nurture: Genetic and environmental influences on behavior. *The Annals of the American Academy of Political and Social Science,* 600**,** 86-98.

PORTER, R. & LEMON, R. 1993. *Corticospinal function and voluntary movement,* Oxford University Press, USA.

PRICE, C., MCCLYMONT, J., HASHMI, F., MORRISON, S. C. & NESTER, C. 2018a. Development of the infant foot as a load bearing structure: study protocol for a longitudinal evaluation (the Small Steps study). *J Foot Ankle Res,* 11**,** 33.

PRICE, C., MONTAGNANI, E., MARTINEZ SANTOS, A., NESTER, C. & MORRISON, S. 2022. Longitudinal study of foot pressures during real-world walking as infants develop from new to confident walkers. *Gait & Posture,* 92**,** 351-358.

PRICE, C., MORRISON, S. C., HASHMI, F., PHETHEAN, J. & NESTER, C. 2018b. Biomechanics of the infant foot during the transition to independent walking: A narrative review. *Gait Posture,* 59**,** 140-146.

PRICE, C., MORRISON, S. C. & NESTER, C. 2017. Variability in foot contact patterns in independent walking in infants. *Footwear Science,* 9**,** S47-S49.

PUTTI, A., ARNOLD, G., COCHRANE, L. & ABBOUD, R. 2008. Normal pressure values and repeatability of the Emed® ST4 system. *Gait & posture,* 27**,** 501-505.

QUIJOUX, F., NICOLAÏ, A., CHAIRI, I., BARGIOTAS, I., RICARD, D., YELNIK, A., OUDRE, L., BERTIN-HUGAULT, F., VIDAL, P.-P., VAYATIS, N., BUFFAT, S. & AUDIFFREN, J. 2021. A review of center of pressure (COP) variables to quantify standing balance in elderly people: Algorithms and open-access code. *Physiological reports,* 9**,** e15067-e15067.

RAI, D. & AGGARWAL, L. 2006. The study of plantar pressure distribution in normal and pathological foot. *Pol J Med Phys Eng,* 12**,** 25-34.

RASHID, U., SIGNAL, N., NIAZI, I. K. & TAYLOR, D. footPress: An Open-Source MATLAB Toolbox for Analysis of Pedobarography Data. 2019 Cham. Springer International Publishing, 361-364.

RAZAK, A. H., ZAYEGH, A., BEGG, R. K. & WAHAB, Y. 2012. Foot plantar pressure measurement system: a review. *Sensors (Basel),* 12**,** 9884-912.

RHEA, C. K., KIEFER, A. W., HARAN, F., GLASS, S. M. & WARREN, W. H. 2014. A new measure of the CoP trajectory in postural sway: Dynamics of heading change. *Medical engineering & physics,* 36**,** 1473-1479.

RICHARDS, J. 2018. *The Comprehensive Textbook of Biomechanics [No Access to Course] E-Book:[Formerly Biomechanics in Clinic and Research]*, Elsevier Health Sciences.

RIDDIFORD-HARLAND, D., STEELE, J. & STORLIEN, L. 2000. Does obesity influence foot structure in prepubescent children? *International journal of obesity,* 24**,** 541-544.

ROBINSON, M. A., VANRENTERGHEM, J. & PATAKY, T. C. 2021. Sample size estimation for biomechanical waveforms: Current practice, recommendations and a comparison to discrete power analysis. *Journal of Biomechanics,* 122**,** 110451.

ROSENBAUM, D. & BECKER, H. P. 1997. Plantar pressure distribution measurements. Technical background and clinical applications. *Foot and ankle surgery,* 3**,** 1-14.

ROSENBAUM, D., WESTHUES, M. & BOSCH, K. 2013. Effect of gait speed changes on foot loading characteristics in children. *Gait & posture,* 38**,** 1058-1060.

RUSU, R. B., BLODOW, N. & BEETZ, M. Fast point feature histograms (FPFH) for 3D registration. 2009 IEEE international conference on robotics and automation, 2009. IEEE, 3212-3217.

SACCO, I. C. N., ONODERA, A. N., BOSCH, K. & ROSENBAUM, D. 2015. Comparisons of foot anthropometry and plantar arch indices between German and Brazilian children. *Bmc Pediatrics,* 15:4.

SAFAEI-POUR, Z., EBRAHIMI, E., SAEEDI, H. & KAMALI, M. 2009. Invesigation of dynamic plantar pressure distribution in healthy adults during standing and walking. *Archives of Rehabilitation,* 10**,** 0-0.

SALAZAR-TORRES, J., MCDOWELL, B., HUMPHREYS, L. & DUFFY, C. 2014. Plantar pressures in children with congenital talipes equino varus—a comparison between surgical management and the Ponseti technique. *Gait & Posture,* 39**,** 321-327.

SAMSON, W., DOHIN, B., DESROCHES, G., CHAVEROT, J.-L., DUMAS, R. & CHEZE, L. 2011. Foot mechanics during the first six years of independent walking. *Journal of biomechanics,* 44**,** 1321-1327.

SEGEV, E., YAVOR, A., EZRA, E. & HEMO, Y. 2009. Growth and development of tarsal and metatarsal bones in successfully treated congenital idiopathic clubfoot: early radiographic study. *Journal of Pediatric Orthopaedics B,* 18**,** 17-21.

SHAFFER, S. W. & HARRISON, A. L. 2007. Aging of the somatosensory system: a translational perspective. *Physical therapy,* 87**,** 193-207.

SIMPSON, J. D., KOLDENHOVEN, R. M., WILSON, S. J., STEWART, E. M., TURNER, A. J., CHANDER, H. & KNIGHT, A. C. 2020. Ankle kinematics, center of pressure progression, and lower extremity muscle activity during a side-cutting task in participants with and without chronic ankle instability. *Journal of Electromyography and Kinesiology,* 54**,** 102454.

SOAMES, R. 1985. Foot pressure patterns during gait. *Journal of biomedical engineering,* 7**,** 120-126.

SPARROW, W., HUGHES, K., RUSSELL, A. & LE ROSSIGNOL, P. 2000. Movement economy, preferred modes, and pacing. *Energetics of human activity***,** 96-123.

STEBBINS, J., HARRINGTON, M., GIACOMOZZI, C., THOMPSON, N., ZAVATSKY, A. & THEOLOGIS, T. 2005. Assessment of sub-division of plantar pressure measurement in children. *Gait & posture,* 22**,** 372-376.

STERGIOU, N. 2020. *Biomechanics and gait analysis,* Academic Press.

SUTHERLAND, D. H., OLSHEN, R., COOPER, L. & WOO, S. L. 1980. The development of mature gait. *J Bone Joint Surg Am,* 62**,** 336-353.

TAX, H. R. 1985. *Podopediatrics,* Baltimore;London, Williams & Wilkins.

TEULIER, C., SANSOM, J. K., MURASZKO, K. & ULRICH, B. D. 2012. Longitudinal changes in muscle activity during infants' treadmill stepping. *Journal of neurophysiology,* 108**,** 853-862.

THELEN, E. 1995. Motor development: A new synthesis. *American psychologist,* 50**,** 79.

TOMASSONI, D., TRAINI, E. & AMENTA, F. 2014. Gender and age related differences in foot morphology. *Maturitas,* 79**,** 421-7.

TONG, J. W. & KONG, P. W. 2013. Reliability of footprint geometric and plantar loading measurements in children using the Emed® M system. *Gait & posture,* 38**,** 281-286.

UNGER, H. & ROSENBAUM, P. D. D. D. 2004. Gender-specific differences of the foot during the first year of walking. *Foot & ankle international,* 25**,** 582-587.

VENKADESAN, M., YAWAR, A., ENG, C. M., DIAS, M. A., SINGH, D. K., TOMMASINI, S. M., HAIMS, A. H., BANDI, M. M. & MANDRE, S. 2020. Stiffness of the human foot and evolution of the transverse arch. *Nature,* 579**,** 97-100.

VERBRUGGEN, S. W., LOO, J. H., HAYAT, T. T., HAJNAL, J. V., RUTHERFORD, M. A., PHILLIPS, A. T. & NOWLAN, N. C. 2016. Modeling the biomechanics of fetal movements. *Biomechanics and modeling in mechanobiology,* 15**,** 995-1004.

VOLPON, J. B. 1994. Footprint analysis during the growth period. *Journal of pediatric orthopedics,* 14**,** 83-85.

WALLACE, J., WHITE, H., AUGSBURGER, S. & WALKER, J. 2021. Development of a method to produce a valid and reliable foot mask for plantar pressure evaluation in children with clubfoot. *Journal of Pediatric Orthopaedics B,* 30**,** 287-295.

WALTHER, M., HEROLD, D., SINDERHAUF, A., KÖRGER, H., KLEINDIENST, F. & KRABBE, B. 2005. Anforderungen an den Kindersportschuh vor dem Hintergrund der Entwicklung des Kinderfußes. *Fuß & Sprunggelenk,* 3**,** 23-33.

WEINSTEIN, S. L. 2000. Bristol-Myers Squibb/Zimmer Award for Distinguished Achievement in Orthopaedic Research: Long-Term Follow-up of Pediatric Orthopaedic Conditions : Natural History and Outcomes of Treatment*†. *JBJS,* 82**,** 980.

WESTCOTT, S. L. & BURTNER, P. 2004. Postural control in children: implications for pediatric practice. *Physical & occupational therapy in pediatrics,* 24**,** 5-55.

WHITTLE, M. W. 2007. *Gait analysis,* Elsevier.

WIDHE, T. 1997. Foot Deformities at Birth: A Longitudinal Prospective Study over a 16-Year Period. *Journal of Pediatric Orthopaedics,* 17**,** 20-24.

WILLEMS, C., CURTIS, R., PATAKY, T. & D'AOÛT, K. 2021. Plantar pressures in three types of indigenous footwear, commercial minimal shoes, and conventional Western shoes, compared to barefoot walking. *Footwear Science,* 13**,** 1-17.

WINTER, D. 2005. Biomechanics and Motor Control of Human Movement, 3rd edn Wiley. *New York.*

WINTER, D. A. 1993. Medial-lateral and anterior-posterior motor responses associated with center of pressure changes in quiet standing. *Neurosci Res Commun,* 12**,** 141-148.

YANG, J., LI, H., CAMPBELL, D. & JIA, Y. 2015. Go-ICP: A globally optimal solution to 3D ICP point-set registration. *IEEE transactions on pattern analysis and machine intelligence,* 38**,** 2241-2254.

YANG, J. F., LAM, T., PANG, M. Y., LAMONT, E., MUSSELMAN, K. & SEINEN, E. 2004. Infant stepping: a window to the behaviour of the human pattern generator for walking. *Can J Physiol Pharmacol,* 82**,** 662-74.

ZEININGER, A., SCHMITT, D., JENSEN, J. L. & SHAPIRO, L. J. 2018. Ontogenetic changes in foot strike pattern and calcaneal loading during walking in young children. *Gait Posture,* 59**,** 18-22.

Thesis glossary

Between-infants registration: data processing technique that register the pressure images /point clouds of one participant onto a template chosen for all participants.

Centre of pressure: the point application of the force/pressure vector during the stance phase.

Contact area: The total area of the foot and/or its regions in contact with the ground during stance phase, expressed in cm^2.

Contact time: the total time the foot and/or its regions spend in contact with the ground over stance, expressed in ms.

Customised automatic mask: a type of mask based on automatic creation and application

Force-time integral: the area under the force-time curve of the foot and/or its regions over stance, expressed in $N.s^{-1}$.

Frames of pressure: the individual pressure images captured from initial contact to foot-off, composing a full pressure step.

Mask: the aggregation of multiple regions of interest created onto the plantar surface of the foot.

Maximum Force: the highest force in the foot and/or its regions during a step cycle, expressed in N.

Maximum pressure picture: the maximum digital pressure image of each step, formed by pixels and containing specific pressure/intensity information.

Pixel: the unit that allows visualising stored and sampled pressure information.

Plantar pressure platform: a technology-based device that uses either resistive or capacitive sensors to capture plantar pressure data.

Plantar pressure trial: the collection of an X number of steps over an X period of time.

Peak Pressure: the singular peak pressure for a single sensor, at a single point in time, across the foot and/or foot region detected during a step cycle, expressed in kPa.

Pressure steps (or steps): digital pressure images resulting from trials of walking.

Pressure-time integrals: The area under the pressure time curve of the foot and/or its regions during stance, expressed in kPa.s^{-1}.

Point cloud: a set of points in 3-D coordinate system xyz.

Registration: the data processing technique that allow transformation of the pressure/point clouds images so that homologous structure can overlap optimally.

Region of interest: a specific area on the steps corresponding to an anatomical area of the plantar aspect of the foot.

Regional analysis (masking analysis): methodological approach to pressure data that divide the steps into regions of interest, which correspond to anatomical areas of the foot.

Pedobarographic statistical parametric mapping: methodological approach for the analysis of pressure data (maximum pressure pictures) that conduct statistical inference at each pixel.

Spatio-temporal analysis of plantar pressures: methodological approach for the analysis of pressure data (frames of pressure composing each step/pressure image) that is analysed in its meaningful spatio-temporal domain, using principles of pedobarographic statistical parametric mapping.

Within-infant registration: data processing technique that register the pressure images /point clouds of one participant onto template chosen for that specific participant.

Works developed from the thesis

Peer-reviewed papers

- **<u>Montagnani E.,</u>** Price C., Nester C., Morrison SC. (2021). Dynamic Characteristics of Foot Development: A Narrative Synthesis of Plantar Pressure Data during Infancy and Childhood. Pediatric Physical Therapy.
  DOI: http://doi.org/10.1097/PEP.0000000000000819
- **<u>Montagnani E.,</u>** Morrison SC., Varga M., Price C. (2021). Pedobarographic Statistical Parametric Mapping of plantar pressure data in new and confident walking infants: a preliminary analysis. Journal of Biomechanics.
  DOI: http://doi.org/10.1016/j.jbiomech.2021.110757
- Price, C., **<u>Montagnani, E.,</u>** Martinez Santos, A., Nester, C., and Morrison, S. (2022). Longitudinal study of foot pressures during real-world walking as infants develop from new to confident walkers. Gait and posture, 92, 351-358.
  DOI: https://doi.org/10.1016/j.gaitpost.2021.12.003 (Contribution to the Great Foundation Project).

Manuscripts under review

- **<u>Montagnani E.,</u>** Morrison SC., Price C., (2022). Masking approaches to analyse plantar pressure data of new and confident walking infants. Selected journal: Gait and Posture.
- **<u>Montagnani E.,</u>** Morrison SC., Price C., (2022). A vector field analysis to investigate foot-ground interactions in infancy during walking. Selected journal: Journal of Biomechanics.

Manuscripts in preparation

- **<u>Montagnani E.,</u>** Morrison SC., Price C., (2022). Exploring changes in plantar pressures and their relationship with body maturation and walking experience. Selected journal: Journal of Biomechanics.

Podium presentation

- **<u>Montagnani E</u>.,** Morrison SC., Nester C., Price C., (2021**).** A preliminary analysis of plantar pressure data in infants at the onset of walking and confidently walking using pedobarographic statistical parametric mapping (pSPM). International Foot and Ankle Biomechanics Conference, Sao Paolo, Brazil; (Online conference).

- **Montagnani E.,** Price C., Nester C., Morrison SC. (2021). Dynamic Characteristics of Foot Development: A Narrative Synthesis of Plantar Pressure Data during Infancy and Childhood. Royal College of Podiatry Conference, Liverpool, United Kingdom, 2022. (Presented by Dr. Stewart C Morrison).
- **Montagnani E.,** Morrison SC., Price C., (2022). A vector field analysis to investigate foot-ground interactions in infancy during walking. 27th Congress of the European Society of Biomechanics, June 26-29, Porto, Portugal.

Poster presentation

- **Montagnani E**., Morrison SC., Nester C., Price C., (2021): The transition from non-weight bearing to independent walking: understanding the role of the foot in the development of walking. 6th Lancaster International Conference on Infant and Early Child Development, Lancaster University.

Appendix 1. Materials for recruitment and data collection

Figure 34. Examples of flyers distributed to local communities, yoga groups, baby centres for infants' recruitment.

Figure 35. Example of poster for infants' recruitment.

Figure 36. Example of flyers summarising information related to the project and data collection procedure.

Longitudinal Participant Information Sheet, GFSS, V6 28th January 2019

Great Foundations – Taking strides in children's foot health

Participant Information Sheet (Longitudinal)

University of Salford MANCHESTER

Small Steps: The development of children's feet

Summary Information

Small Steps is one of the research projects in the Great Foundations initiative. Our goal is to understand how babies' feet grow and develop as they learn to walk.

Through this time we will study:

- Foot size and shape
- Skin thickness, elasticity and texture
- Muscle shape, size and activity
- Footprints and movement patterns

What will it involve?

If you take part in the Small Steps study you and your baby will be invited to visit our baby space up to four times during this exciting period in your baby's development:

- First visit – when your baby can support their own head and reach for their feet when lying on their back.
- Second visit – when your baby can pull themselves to standing.
- Third visit – when your baby can take up to 5 steps on their own.
- Last visit - when your baby is a confident, balanced, stable, independent walker.

Each visit will last up to 2 hours and you will receive money as a thank you for your time. This study has obtained ethical approval from both Universities of Brighton and Salford.

Where will it take place?

The visits will take place at our baby space at the University of Salford (Frederick Road Campus).

How can I find out more information?

Please read the full information sheet, which follows. This will ensure that you fully understand everything that taking part in this research study will involve. Contact details are provided at the end.

Longitudinal Participant Information Sheet, GFSS, V6 28th January 2019

Small Steps: The development of children's feet

Your child is being invited to take part in a research study. Before you decide whether or not you are happy for them to participate you need to fully understand the study and why it is being conducted. Please take time to read the following information carefully, which will describe the study to you. Ask any questions regarding the study and take time to decide whether or not you want your child to participate in this research project.

What is the purpose of the study?

This study is to measure the changes to infant feet and walking style from sitting to walking confidently on their own. The transition to independent walking in infants has rarely been researched. The study will allow the researchers provide large scale data on how the foot skin and muscles as well as the walking style of infants change across these important developmental milestones.

Why have we been invited?

You have been sent this information sheet as you have volunteered yourself as a parent or guardian of a child who may be suitable to take part in this research. It is also important that these infants reached developmental milestones within a month of the expected stage, which we will check with you, but assessing development is not our aim.

Do we have to take part?

It is up to you to decide whether you are happy for your child to take part in this research as it is voluntary and you are providing consent on their behalf. We will describe the study and go through the information sheet with you, which we will give to you. We will then ask you to sign a consent form to show you agree for them to take part. You are free to withdraw them at any time, without giving a reason to the research team, even once your child has started the research study in the laboratory. If this is the case their data may still be used within the research and within resulting publications unless you explicitly tell us not to do so.

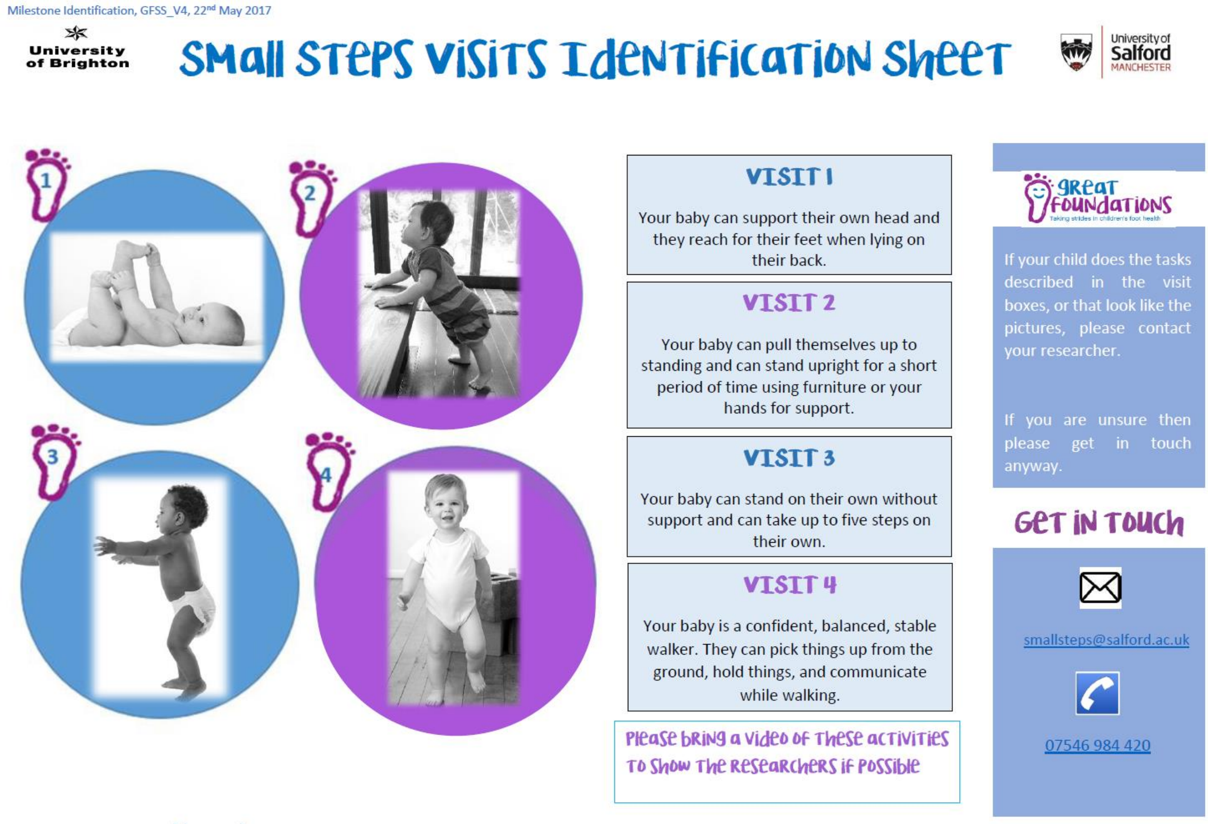
What will happen to us if we take part?

If you agree for your child to take part in this research then you will attend the University of Salford with them on four occasions. You will both participate in four data collection sessions within the Brian Blatchford Building lasting 1-2 hours each, including some time for breaks. This is in a private space setup specifically for this study on infants. You will be present throughout.

There will be times for resting, feeding, changing and nappy changing facilities and toilets will be readily accessible. The room will be decorated like a nursery and there will be a safe environment with seating for yourself.

Data collected during your four visits will include your child's foot size and shape, characteristics of the skin on their feet and legs (how textured, elastic, hydrated and thick it is), and their muscle size and structure. We will also measure how they move and the pressure they experience on the sole of their feet during movement and when still.

Figure 37. Example of information sheet used to help parents identifying the milestones required for data collection.



Appendix 2. Synthesis of plantar pressure studies

Table 11. Summary of typically developing plantar pressure studies during infancy.

Authors (year of publication)	**Study design**	**Age group and sampling**	**Plantar pressure technology**	**Testing protocol**	**Nature of trials**	**N of trials and/or steps tested**	**Data analysis approach**	**Pressure variables (and units)**
Bosch et al., (2010)	Longitudinal	14 – 18 months of age and recruited by developmental milestones	Emed ST, Emed X (Novel, GmbH, Munich)	Self-selected speed, free walking. Each participant analyzed over 9 years	Supported and independent walking trials	5 steps for both left and right foot per participant	Regional analysis (heel, midfoot, forefoot, hallux and toes)	PP (kPa), MaxF (% BW), CA (% Total foot CA), AI

Bertsch et al., (2004)	Longitudinal	14 – 16 months of age and recruited by developmental milestones	EMED ST4 (Novel, GmbH, Munich)	Self-selected speed, free walking. Each participant analyzed 4 times over one year	Supported and independent walking trials	5 steps for both left and right foot per participant	Regional analysis (heel, midfoot, forefoot, hallux and toes)	PP (kPa), FTI (Ns), CA (cm2), MaxF (N), CT (ms), CT (% Stance) (all values also normalized to foot size and BW)
Hallemans et al., (2003)	Longitudinal	Age not specified. Independent walking 0-2 months	Footscan platform (RS scan International) + AMTI force plate	Self-selected speed directed walking. Each participant analyzed 2 times in 6 weeks	Not reported	Not reported	Regional analysis (Heel, midfoot, lateral central and medial metatarsal heads, hallux)	PP (kPa), FTI (%Total foot FTI), CoP
Hallemans et al., (2006)	Longitudinal	Age not specified, recruited within a week	Footscan platform (RS scan International	Self-selected speed, free walking. Each participant	Independent	1 step per participant	Not reported	PP (kPa), FTI (%Total foot FTI), CoP

		of 2/3 independent steps	) + AMTI force plate	analyzed 10 times in 20 weeks				
Muller et al., (2012)	Cross-sectional	12-24 months of age and recruited by age	EMED X (Novel, GmbH, Munich)	Self-selected speed directed walking. Each participant analyzed once at each age	Independent	3 to 5 steps per participant	Regional analysis (heel, midfoot, forefoot defined using 27% and 55% of the foot total length from heel to toes)	PP (N/cm2), FTI (Ns), CA (cm2), AI
Alvarez et al., (2008)	Cross-sectional	Infants aged less than 24 months of age (mean age 1.56 years) and	Tekscan HR Mat (South Boston, MA)	Self-selected speed directed walking. Each participant analyzed once	Not reported	3 steps per participant	Regional analysis (heel, lateral and medial midfoot, lateral and medial forefoot)	% of force across the regions, % of stance spent across the regions

		recruited by age						
Henning and Rosenbaum (1991)	Cross-sectional	14 – 32 months of age and recruited by age	EMED F01 (Novel, GmbH, Munich)	Self-selected speed, free walking. Each participant analyzed once	Not reported	3 steps per participant	Regional analysis (medial and lateral heel, midfoot, metatarsal 1,3 and 5, hallux)	PP (kPa), FTI (%Total FTI)

Table 12. Summary of typically developing plantar pressure studies during infancy.

Authors (year of publication)	Study design	Age group and sampling	Plantar pressure technology	Testing protocol	Nature of trials	N of trials and/or steps tested	Data analysis approach	Pressure variables (and units)
Bosch et al., (2010)	Longitudinal	2 – 10 years of age and recruited by developmental milestone	Emed ST, Emed X (Novel, GmbH, Munich)	Self-selected speed, free walking. Each participant analyzed 17 times over 9 years	Supported and independent walking trials	5 steps for both left and right foot per participant	Regional analysis (heel, midfoot, forefoot, hallux and toes)	PP (kPa), MaxF (% BW), CA (%Total foot CA), AI
Kellis (2001)	Cross-sectional	3 years of age and recruited by age	Musgrave pressure platform system	Self-selected speed directed walking. Each participant analyzed once	Independent	1 steps per participant	Regional analysis (heel, lateral and medial midfoot, medial central and lateral metatarsal	PP (kPa) and mean PP

							heads, hallux, second to fifth toes)	
Phethean and Nester (2012)	Cross-sectional	4 to 7 years of age and recruited by age	Biokinetics dynamic optical pedobarograph (Biokinetics Inc., Bethesda, USA),	Self-selected speed directed walking. Each participant analyzed once	Independent	5 steps for both left and right foot per participant	Regional analysis (heel, lateral and medial midfoot, hallux, metatarsal heads 1-5)	PP (kPa), FTI (Ns),
Phethean and Nester (2014)	Cross-sectional	4 to 7 years of age and recruited by age	Biokinetics dynamic optical pedobarograph (Biokinetics Inc., Bethesda, USA),	Self-selected speed directed walking. Each participant analyzed once	Independent	1 steps per participant	Two regional analysis approaches (1. heel, midfoot, forefoot, hallux and toes; 2. medial and lateral heel,	PP (kPa)

							medial and lateral midfoot, first to fifth metatarsal heads, hallux and toes)	
Muller et al., (2012)	Cross-sectional	2 to 13 years of age. Each age corresponding to an age group and recruited by age	EMED X (Novel, GmbH, Munich)	Self-selected speed directed walking. Each participant analyzed once at each age	Independent	3 to 5 steps per participant	Regional analysis (heel, lateral midfoot, medial midfoot, hallux, and first, second, third, fourth and fifth metatarsal heads)	PP (N/cm2), FTI (Ns), total foot CA (cm2) only, AI

Alvarez et al., (2008)	Cross-sectional	3 to 7 years of age divided in 2 groups (2-5; older than 5) and recruited by age	Tekscan HR Mat + Research Foot Module (South Boston, MA)	Self-selected speed, directed walking Each participant analyzed once	Not reported	3 steps per participant	Regional analysis (total foot, heel, midfoot, forefoot)	MaxF (%BW) % of stance spent across the regions
Henning and Rosenbaum (1994)	Cross-sectional	6 to 10 years of age and recruited by age	EMED F01 (Novel, GmbH, Munich)	Instructed walking, speed (1.0 meters/sec). Each participant analyzed once	Independent	5 steps per participant	Regional analysis (medial and lateral heel, midfoot, first, third and fifth metatarsal heads, hallux)	PP (kPa), FTI (%Total foot)
Mesquita et a., (2018)	Cross-sectional	4 to 10 years of age and recruited by age	Emed AT-4 (Novel GmbH, Munich, Germany)	Self-selected speed directed walking. Each participant analyzed once	Independent	5 steps for both left and right foot per participant	Regional analysis (heel, midfoot, forefoot, hallux and toes)	PP (kPa), MaxF (% BW), CA (cm2)

Abbreviations: PP, peak pressure; CA, contact area; CT, contact time; FTI, force-time integral; CoP, center of pressure; MaxF, maximum force; % total, relative to the total variable selected; % BW, relative to the subjects' body weight; % stance, relative to the full stance phase; AI, arch index

Appendix 3. Differences between left and right feet

Figure 38. (A) Mean (cm) and standard deviation (shades) of absolute anterior-posterior (AP) trajectories of left feet (red dashed line) and right feet (black line) at the onset of walking, temporally normalised to 101. (B) Nonparametric SPM1d paired t-test for comparison of the AP COP trajectory between left and right feet at the onset of walking.

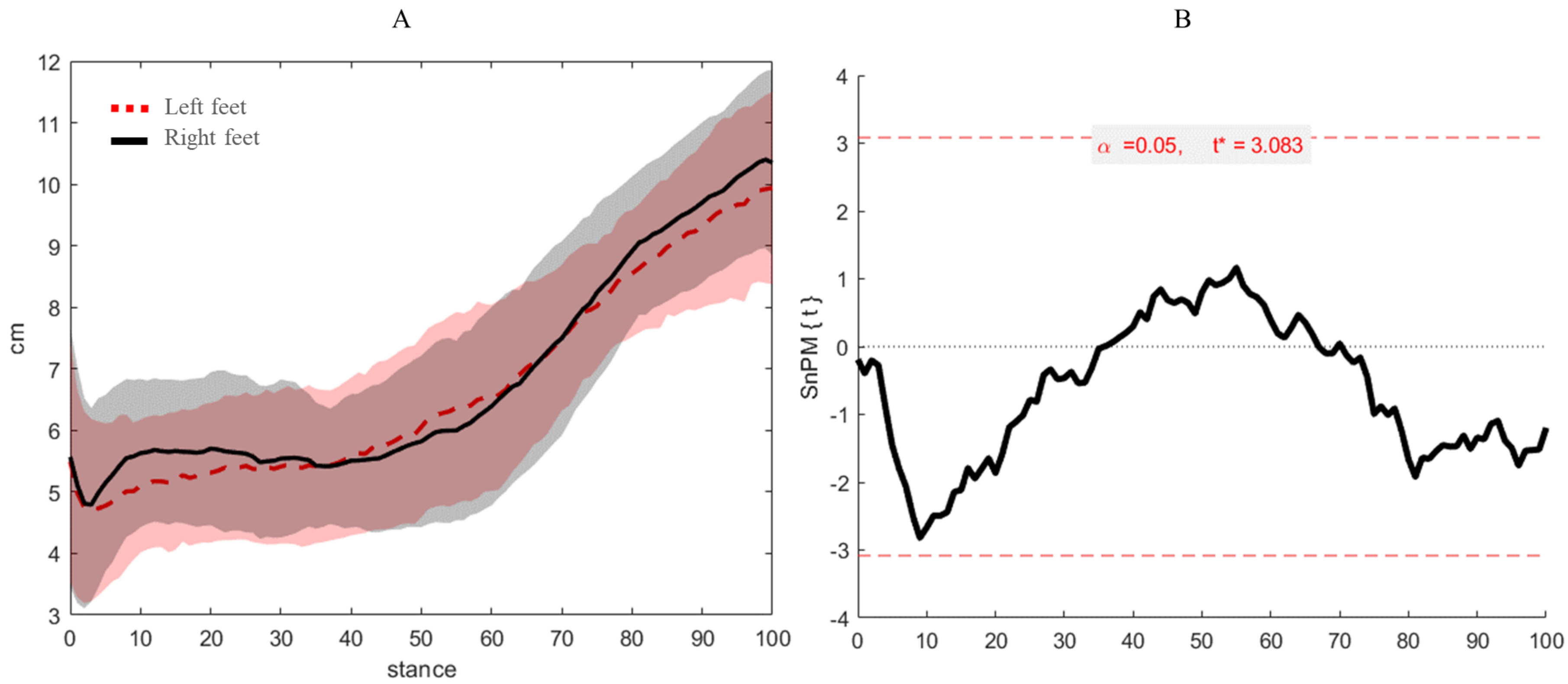


Figure 39. (A) Mean (cm) and standard deviation (shades) of absolute anterior-posterior (AP) trajectories of left feet (red dashed line) and right feet (black line) of confident walkers, temporally normalised to 101. (B) Nonparametric SPM1d paired t-test for comparison of the AP COP trajectory between left and right feet of confident walkers.

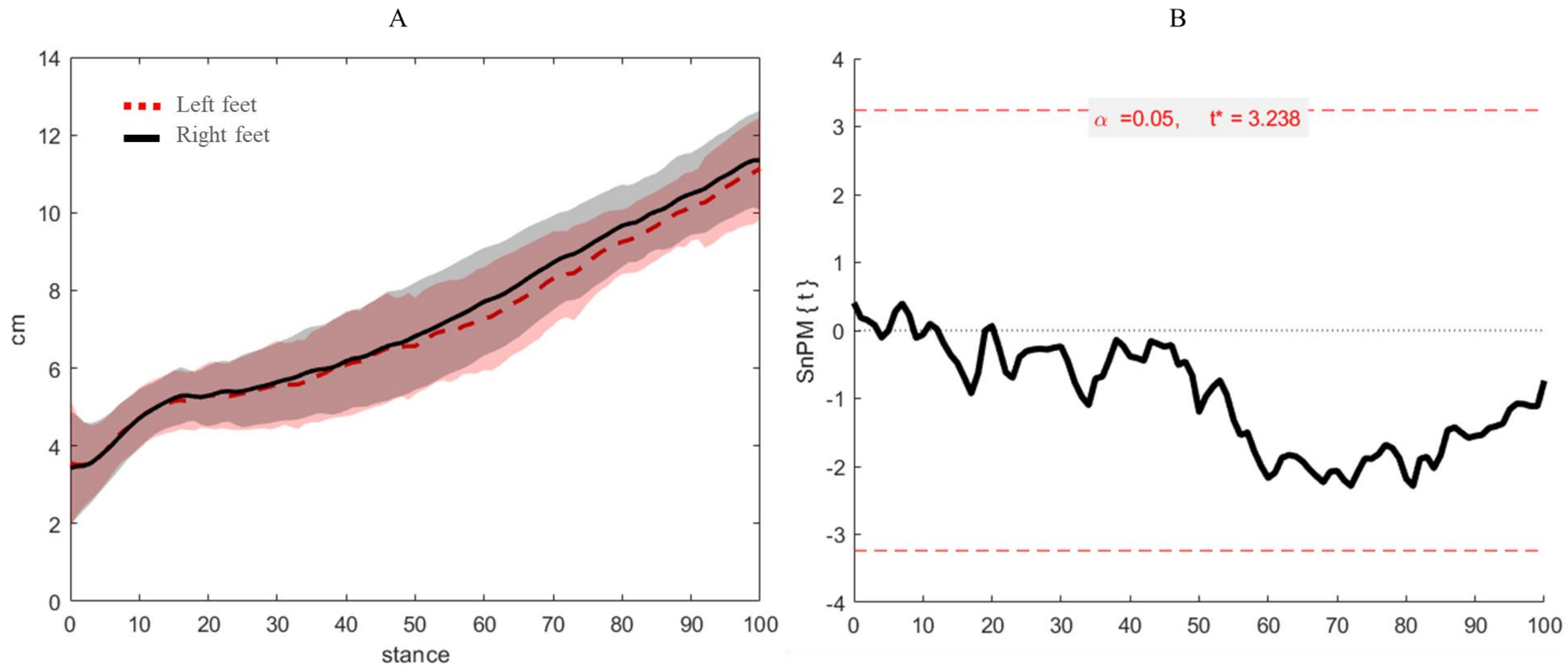


Figure 40. (A) Mean (cm) and standard deviation (shades) of absolute medio-lateral (ML) trajectories of left feet (red dashed line) and right feet (black line) at the onset of walking, temporally normalised to 101. (B) Nonparametric SPM1d paired t-test for comparison of the ML COP trajectory between left and right feet at the onset of walking.

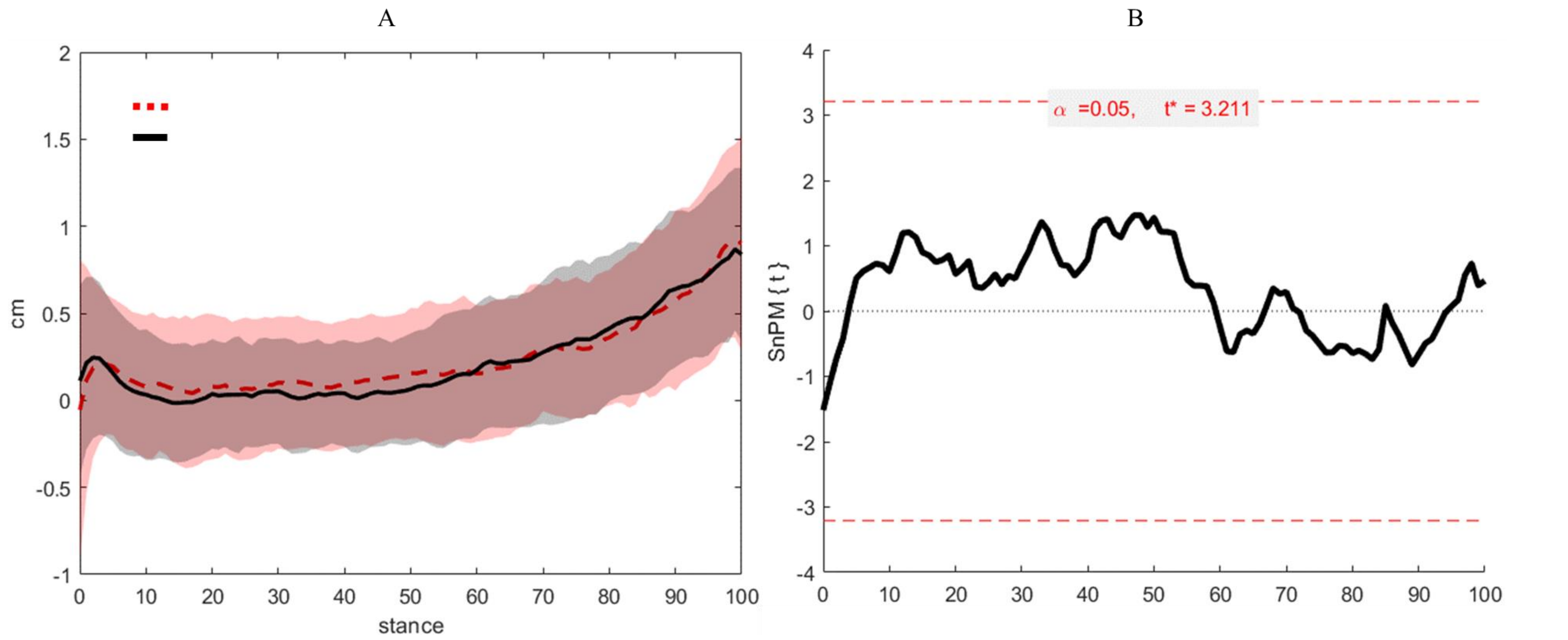


Figure 41. (A) Mean (cm) and standard deviation (shades) of absolute medio-lateral (ML) trajectories of left feet (red dashed line) and right feet (black line) of confident walkers, temporally normalised to 101. (B) Nonparametric SPM1d paired t-test for comparison of the ML COP trajectory between left and right feet of confident walkers.

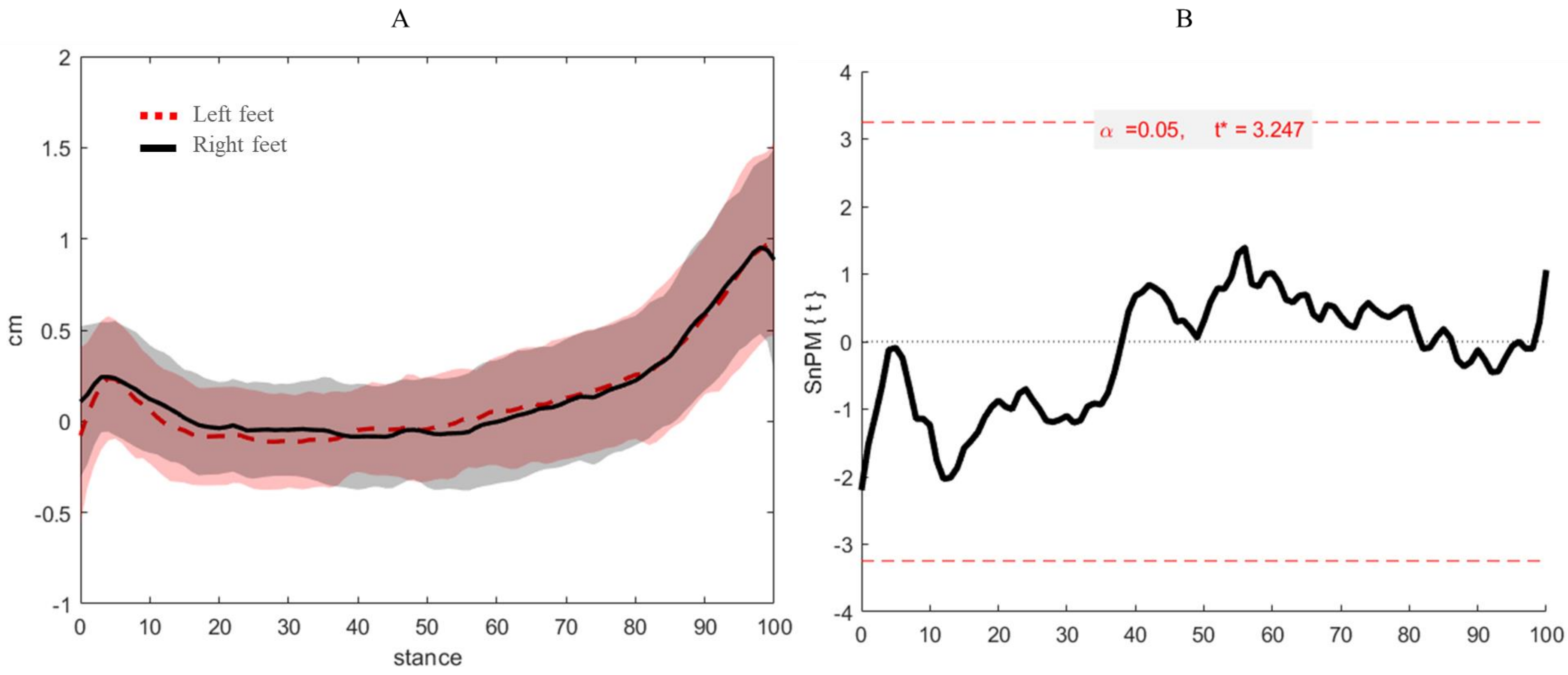
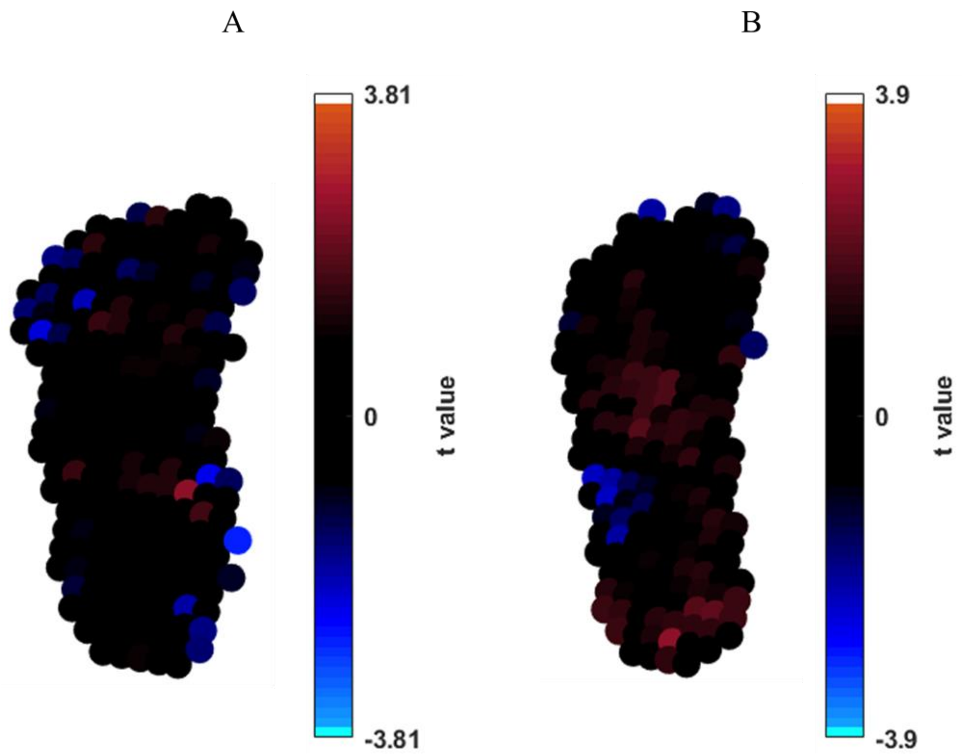


Table 13. Comparison of mean path lengths and velocities at the onset of walking (V2) and confident walking (V3) between left and right feet.

	AP mean path lengths (V2)	**AP mean path lengths (V3)**	**AP mean velocity (V2)**	**AP mean velocity (V3)**	**ML mean path lengths (V2)**	**ML mean path lengths (V3)**	**ML mean velocity (V2)**	**ML mean velocity (V3)**
Z	-.149[b]	-.595[b]	-.151[c]	-.127[c]	-1.138[b]	-.624[b]	-.399[c]	-.352[c]
Asymp. Sig. (2-tailed)	.882	.552	.880	.899	.255	.532	.690	.725

Figure 42. Nonparametric pSPM paired t test for comparison of plantar pressure between left feet and right feet in V2 (A) and in V3 (B).



Appendix 4. Normality tests

Figure 43. Normality test of absolute anterior-posterior (AP) trajectories, considering the residuals (middle panel).

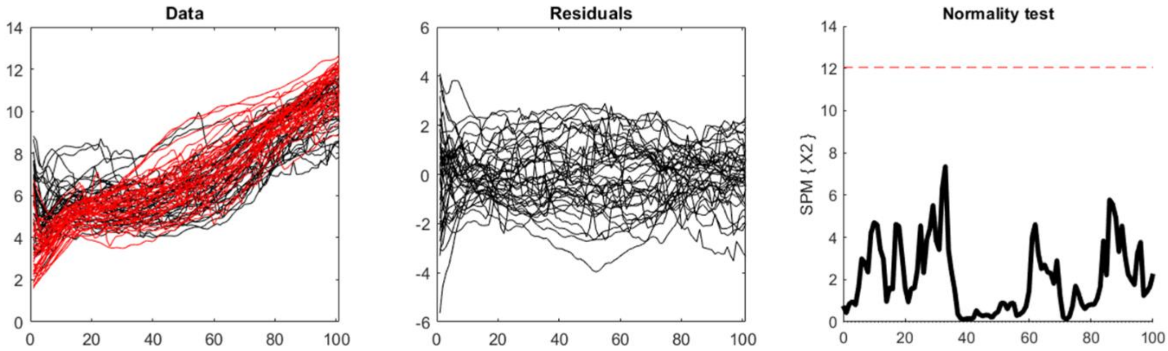


Figure 44. Normality test of normalised anterior-posterior (AP) trajectories, considering the residuals (middle panel).

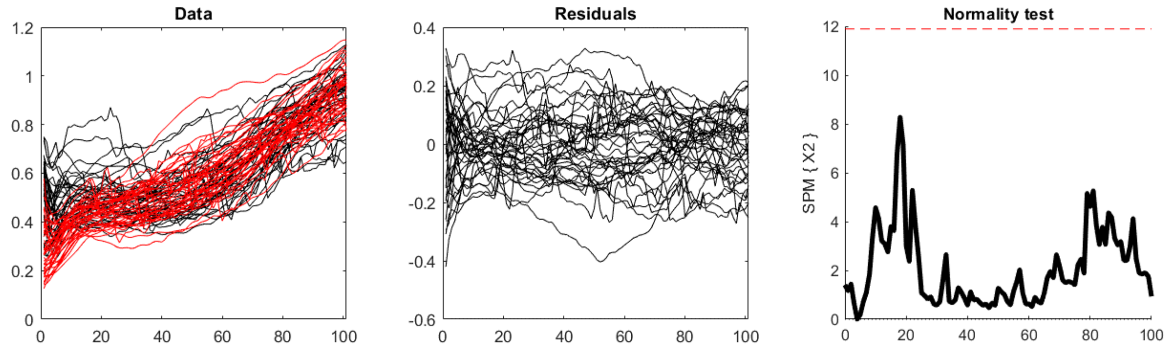


Figure 45. Normality test of absolute medio-lateral (ML) trajectories, considering the residuals (middle panel).

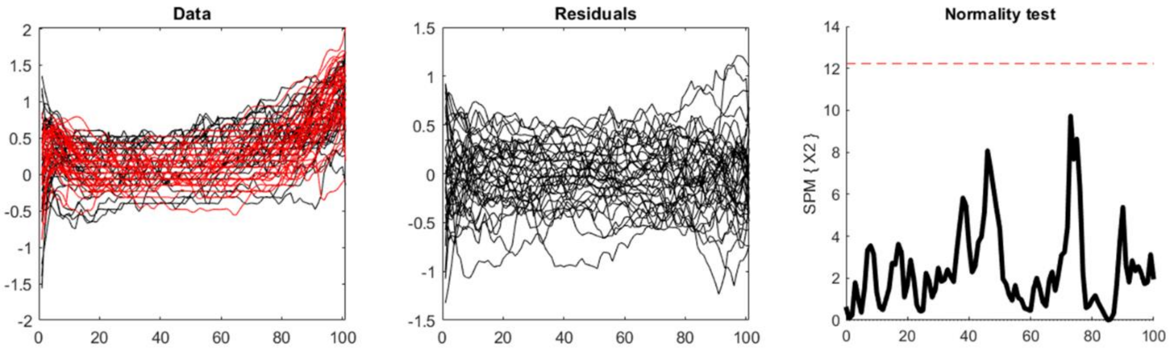


Figure 46. Normality test of normalised medio-lateral (ML) trajectories, considering the residuals (middle panel).

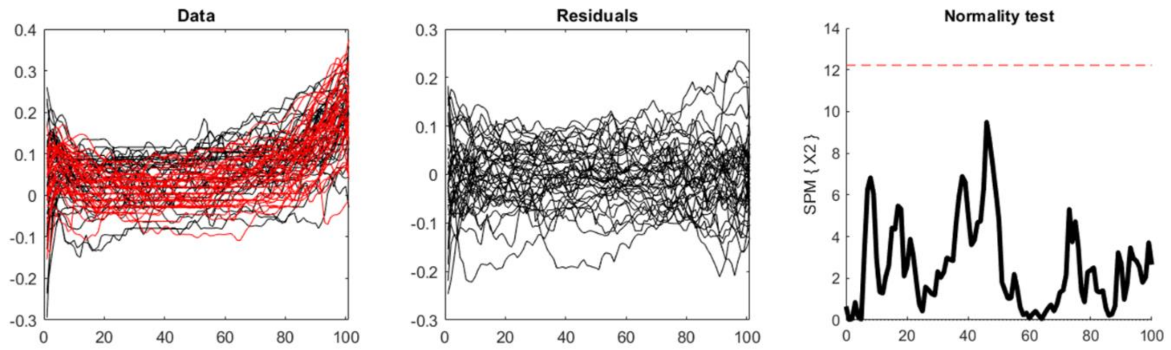


Table 14. Normality test with the Shapiro-Wilk test on absolute and normalised mean path lengths and velocities of the centre of pressure.

	Variables	Statistic	Sig.
Absolute values	AP mean path length	.817	.000
	ML mean path length	.940	.001
	AP mean velocity	.960	.016
	ML mean velocity	.879	.000
Normalised values to foot lengths and widths	AP mean path length	.830	.000
	ML mean path length	.937	.001
	AP mean velocity	.954	.007
	ML mean velocity	.842	.000