Biomechanics of the infant foot during the transition to independent walking: a narrative review

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Abstract

Recognising structural and functional development of the paediatric foot is fundamental to ensuring a strong theoretical framework for health professionals and scientists. The transition of an infant from sitting to walking takes approximately 9 months and is when the structures and function of the foot must respond to the challenges of bearing load; becoming increasingly more essential for locomotion. Literature pertaining to the phase of development was searched. A narrative approach synthesised the information from papers written in English, with non-symptomatic infant participants up to the development stage of independent walking or two years of age. A range of literature was identified documenting morphological, physiological, neuromuscular and biomechanical aspects of the infant within this phase of development. The progression of variable gait to a regular pattern is documented within a range of studies focusing on neuromuscular control and ambulation development. However, methodological approaches may have compromised the external validity of such data. Additionally, limited consideration for the specific function and development of the foot is evident, despite its role as the primary site of weight bearing and interface with the floor. A lack of consideration of infants prior to ambulation (i.e. before cruising or walking) is also apparent which prevents a reference baseline being used effectively. This review also identifies future research priorities such that a comprehensive understanding of foot development from a non-weight bearing to a weight bearing structure during locomotor advancement can be gained.

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Introduction

The phases of infant development from sitting to walking independently represents a timeline of important milestones in the development of motor control and co-ordination (1–3). It is a key stage of development where the anatomy and neuromuscular and sensory systems are undergoing rapid changes. These impact substantially on the infant's ability to undertake tasks which require strength, balance and coordinated movement patterns such as standing and walking. Throughout this phase different locomotor strategies exist; while *cruising* the infant uses external surfaces to transition sideways, during *supported walking* the infant requires external support to ambulate and in *independent walking* the infant can walk by themselves (4–6). Infants progressively become more mobile more frequently and for longer each day (7). Alongside central neuro-developmental changes, the feet are important structures which support infants to explore, interact and investigate their physical and social environments. The shape, structure and function of the foot continues to change throughout infancy as the foot develops as a weight bearing structure from an organ primarily used for reaching (8,9). Despite this, precise changes to foot morphology, structure and function are yet to be quantified during the infant stage and longitudinal studies following cohorts of infants into childhood are yet to be undertaken. Understanding the physiological and biomechanical changes which occur during infancy is an important baseline for ensuring that pathways to the development of foot problems and/or foot pathologies are underpinned by a contemporary and progressive evidence base.

The nature of infant morphology and anatomy at the onset of locomotion has been considered, generally through quantification of body dimensions (10,11) and composition (12). Body weight more than doubles from birth to the infants first birthday and the lengths of the lower limb increases by nearly 50% in a linear manner from birth to 18 months of age (13). The development of foot anatomy is complete upon the full ossification and skeletal maturing, which happens progressively in the bones of the foot. The ossification of the tarsal commences with the calcaneus, followed by the cuboid then navicular (14,15). These underlying skeletal developments occur within a foot characterised by a flat arch profile, with large contact areas and high levels of subcutaneous fat. Bertsch et al, (16) proposed that 50% of the final foot length is achieved by 12 – 18 months of age, disproportionately high when compared to body length. Foot contact area increases as the infant foot grows (16,17), which may help to increase the stability of the infant by increasing the relative size of the base of support and may also reduce plantar pressures (18,19). This will also influence the local loading of the soft tissue of the

foot as research considering tissue adaptation alludes to weight-bearing being functionally significant to maintenance of tissue status (19,20).

Investigation of walking kinematics, kinetics (22-24) plantar pressures (16,25) and muscle activity (26) has been undertaken in infants once walking. These studies generally start data collection at, or within a few months, of walking onset and report increases in coordination and reductions in variability over time and into childhood. Longitudinal changes in gait kinematics and plantar pressures once the infant is weight-bearing and walking independently have been documented (16,23). Additionally, some cross-sectional studies report functional differences in locomotion at different developmental milestones (e.g. initiation of independent walking and experienced independent walking) or ages (20,27). However, existing study designs generally commence at the cruising or supported walking phase and not before ambulation is initiated, therefore longitudinal data spanning the onset of gait in infants and documenting kinematic developments through cruising and walking does not exist. Changes in plantar pressure magnitude and distribution suggest that significant demand on the plantar skin and musculoskeletal structures occurs as gait matures (18,25).

Collating and reviewing literature relating to the development of gait in infants can expose key gaps in the existing literature and thus help determine research priorities related to infant foot development. Furthermore, this information is fundamental to help inform parents, clinicians and other stakeholders as to the nature of the changes to the foot and lower limb structure and function during this key time in development. This review aims to summarise and critique existing **literature** quantifying biomechanical characteristics (temporal-spatial characteristics, plantar pressures, lower limb electromyography (EMG) and kinematics) in infant cruising, supported and independent walking.

Methods

A narrative (as opposed to a systematic) literature review was chosen due to the aim to summarise and critique literature and due to the diverse nature and small number of research papers with relevant content. As the basis of our review a literature search was undertaken with the last date for paper inclusion being August 2016 using PubMed, Google Scholar and Science Direct search engines. Within these search engines the terms

"infant"/"child" were combined (using AND) with terms such as "developing gait", "gait development", "foot development", "foot growth", "foot pressure", "muscle activation", "foot" and searched.

Articles were filtered and citations and patents were excluded. No restriction on year of publication was imposed to capture as many publications relating to infant feet as possible. Additionally, reference lists from identified literature were manually searched for completeness. From this pool of potential papers criteria were used to filter for suitability to be included in our review: written in English (5 excluded); involving non-symptomatic infant participants (60 excluded); and infants of up to developmental stage representing experienced independent walking or aged maximum two years (68 excluded). Exclusion and further screening removed papers that were abstracts with no data (3 excluded); or involved tasks which did not load the foot in a quantifiable manner such as grasping (12 excluded).

Papers meeting the inclusion criteria were then manually screened to confirm content related to the development of the infant foot, specifically; descriptive characteristics of infant motion, loading of the infant foot, or kinematics and electromyography of infant lower limb motion. To support the findings from the synthesised literature, the detail of twelve papers was collated in tables for presentation and inclusion alongside the narrative sections of the manuscript. This detail included extraction of information related to the location of the study, the number of participants, the developmental stage of the participants, the study design, measurement timing and outcome variables.

Descriptive Characteristics of Infant Motion

As motor control and physical capacity develops, infant's locomotion strategies adapt in their manner, achievement and their variability. The temporal-spatial characteristics of these strategies alters the manner in which the foot is loaded i.e. there is an increase in number of steps (28), a change in the loading on the plantar surface (18). This demonstrates the nature of the growing demand on the foot as a support structure. Data describing milestones prior to independent walking has quantified postural control in sitting (29,30) and the kinematics of crawling (31). Early independent walking is characterised by an average short step length of around 0.12 m and a low velocity of around 0.24 m.s^{-1}, which increases with experience over the first few months of walking towards 0.25 m and 0.80 m.s^{-1} respectively (26,32). These data are from prescriptive environments

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where the infant was encouraged to walk in a specific direction. Despite this potentially artificial and controlled environment, variation in outcome variables was large. For example the range of normalised step length recorded by Badaly and Adolph was 0.31-1.09 *leg length from 164 infants (32). In contrast, observational studies provide a more natural environment for infants and is less likely to alter their walking (e.g. by affixing markers to the skin or constraining walking to a specific direction). These are more externally valid and allow for larger participant numbers and a true quantification of natural behaviour. At onset, independent walking in infants is highly variable both between steps of the same infant (27,33) and between infants of the same developmental stage or age (35). With reference specifically to spatial characteristics infant gait is more variable in step length than step width, which reverses with walking experience and the maturation of motor control to match the adult pattern (whereby step width is more variable than length) (33).

In behavioural sciences research, gait "bouts" refer to the number of steps undertaken in a phase of walking; with 1-3 steps being common for 13 month olds (77.3% of walking bouts were <4 steps) (28,34). As infants develop and become more experienced, longer gait bouts become more frequent (59.8% of walking bouts were <4 steps at 19 months) (34), walking duration increases (r = .28, p <.01) and the rate of falls per hour decreases (r = -.33, p<.01) (28). This literature, in addition to demonstrating the progression of an infant, suggests that steps in a straight line is not a common activity for infants at this stage of development. As such, data collection that contrives walking (e.g. in a straight line across a pressure platform) may not be relevant until the infant is a more experienced independent walker. Even then, however, it is likely that this behaviour only reflects a small number of their walking bouts; 19 month old infants with mean walking experience of 192 days have a probability of .61 of stopping within 5 steps of gait initiation (34). This is a significant limitation that needs to be considered when interpreting the existing research, including that which follow relating to loading of the infant foot and gait kinematics.

Loading of the infant foot

Pressure distribution across the plantar surface of the foot is used to quantify load applied to the sole of the foot and has been investigated in children from around one year of age and after independent walking has been established (18,19,25) (Table 1). The resolution of the pressure platform and therefore the data, range from 3.5

to 4 sensors.cm^{-2} (Table 1). Due to the smaller foot size in infants this results in a resolution that is comparatively lower than that achieved on an adult foot with the same technology. However, this resolution is equivalent to adult data collected on some of the lower resolution pressure platforms utilised for research and therefore can be considered sufficient for comparison.

A combination of longitudinal and cross-sectional research exists reporting plantar pressures, contact times and contact areas in infants who are new to independent walking and, in particular, how these change as the foot and walking develop (Table 1). It is widely reported that early walking is characterised by a flat-foot contact as opposed to a heel contact (16,36). However, research points to a varied initial foot contact with either the heel (5% of footfalls), forefoot (60%) or full foot (35%) in 10 infants within one week of being able to take 2-3 steps independently (37). Within this group this altered after 8 weeks of independent walking to be dominated by initial heel contacts (58%), a result that is supported by kinematic data from a larger group of participants (N = 186) where over 30% of individuals walked with an initial heel contact at one year of age (38). Consistent initial heel contact is generally observed by one year after the onset of independent walking (39). That this contact pattern changed over 8 weeks reflects the significant speed of developmental change, which poses specific challenge for researchers wishing to identify and measure changes across such short epochs.

Similarly, as a heel-toe contact pattern develops, findings from cross-sectional research demonstrate a shift in pressure distribution from the midfoot in younger infants to the heel and forefoot in children (40). In this research the stage of ambulatory development of the participants was not recorded. When considering pressure variables, it has been demonstrated that the covariate of age of walking onset does not significantly alter relative contact area, arch index, peak pressure or relative maximum force in developing infants when they were grouped by walking experience (41). Thus developmental stage is more important than chronological age in terms of walking development, and studies should utilise this variable to define cohorts (7). Despite this methodological weakness, the shift in pressure from midfoot to heel and forefoot is consistent with findings from longitudinal research. Bertsch et al., demonstrated that the relative contact time in the midfoot reduces from 75.8% to 65.4% of the gait cycle and midfoot load from 30% to 20% of the total impulse on the plantar foot surface from the onset of independent walking to 6 months later (16). These findings have been attributed to the osseous development of the medial longitudinal arch (16), as well as increased stability reducing the requirement to load the midfoot for increased contact area and muscular control (23). Alongside a shift toward

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initial heel contact, a lateral shift in load bearing is evident with increasing walking experience, evidenced by the more lateral deviation in the centre of pressure under the developing foot (25). This is consistent with reduced pressures under the Hallux and reductions in loading in the midfoot and development of the anatomical structures which form the longitudinal arches of the foot. The trajectory of the centre of pressure warrants further investigation from earlier forms of walking such as cruising through to independent walking as it can provide information relating to neuromuscular control and stability (42), which would infer the development of motor control through infancy.

Other characteristics of infant gait include high contact areas (relative to body weight) and low absolute plantar pressures compared to older children (18,19,43). The plantar pressures in the infant who has been walking independently for 0-2 months are a magnitude of 25-50% of what will be experienced as an adult (25). This has been attributed to the increased subcutaneous fat on the infant foot, lower body-weight to foot contact area ratio, the immature skeleton and the lower walking speeds in infants (16,25,44). In the infant foot the greatest pressures occur under the hallux, which appears to be consistently reported for at least the first 3-6 months of independent walking (16,25,41,43) (Table 1). Peak pressure under the hallux range between approximately 120-180 kPa in infants who have been walking independently (2-3 metres without support) for 1-8 months (16,19,25).

As evident in the above research a range of research has quantified plantar pressures in independent walking. Some of these studies report high participant numbers (Table 1), which were required due to both the high intra- and inter-individual variability (both of which did not reduce across the first year of independent walking (16)); and the large number of variables which were statistically compared. However, the pressure data was collected as infants walked in a straight line with concurrent steps and thus is not representative of real world infant activity and therefore the real pressures being applied to the infant foot during cruising and supported walking in particular. Due to the inconsistent foot trajectory (22) and irregular placement of the infant foot into and around objects, it is expected that pressures on the lateral borders and apices of the toes are relevant in terms of proprioceptive feedback, particularly in the early stages of weight bearing. Understanding these could be key to explaining the development of motor control and learning processes during the earliest experiences of upright ambulation and thus transition from cruising to supported walking. Such data is currently absent. Furthermore, the existing data is largely European (German specifically, Table 1) and from convenience

samples (16,19,37), without consideration for the influences of ethnicity, obesity and wider population characteristics. Addressing these issues may offer more insight to help define how pressures on the soft tissues of the foot alter whilst infants transition from non-weight bearing to cruising, supported and independent walking.

Motion of the infant

Studies evaluating the kinematics of the foot and lower limbs of infants and children define the foot as both single- (23) and multi-segment, the latter of which has only been implemented in older children (45). Multi-segment foot models have not been utilised in the kinematic assessment of the infant foot, perhaps due to the greater subcutaneous fat of the infant, assumptions involving rigidity of the anatomically immature foot segments, the small size of the foot and the practical difficulties of testing infants (e.g. marker affixation, inability to follow instruction). To fully understand the infant foot therefore further work to define a feasible methodology and determine the feasibility and validity needs to be undertaken, with consideration of existing findings in older children (46,47).

Whilst infant foot kinematics during gait have received limited detailed attention, whole body kinematics have been reported from early walking to experienced walking in infants (Table 2). One study has considered the kinematics at the ankle and the metatarsophalangeal joints in walkers aged from 1.2 - 31.0 years (48). Despite joint ranges of motion not differing between groups, a trend for greater ankle eversion moment (-0.04 $N.m/m._0g.l_0$ compared with <-0.03 $N.m/m._0g.l_0$) was evident with younger aged groups (mean age of 2.1 years) (48). A more controlled comparison of populations may have enabled this study to identify more significant differences in younger walkers. Comparing infant gait to the gait of older children or adults reduces the statistical power to identify differences between developmental stages in infants for example. Both longitudinal and cross-sectional kinematic studies in infants with more walking experience have identified increased knee and hip flexion/extension range of motion and increased dorsiflexion at the ankle (23,38,49). Alongside kinematic changes, research points to joint kinetics at the ankle displaying significant maturation as infants become more experienced walkers, with a doubling of power generation ($w.kg^{-1}$) at the ankle at push off

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into adulthood (23). Which is consistent with an earlier study of 27 one year olds where an immature gait pattern was displayed at the ankle with plantarflexion at initial contact and reduced dorsiflexion in swing (38).

The influence of footwear on the specific motion of the foot in infants has not been investigated. Most studies do not report specifically, but appear to have been undertaken barefoot (Table 2), with one study reportedly used a soft sock for marker attachment (23). The attire of the infant has been investigated and trousers and nappy conditions have been shown to alter basic gait patterns in infants with 6-18 months of walking experience, specifically walking velocity and step length (50). Clothing, footwear and surfaces are likely to have an influence on the infant both in terms of mechanical and proprioceptive effects, but despite this these conditions are rarely reported in research studies (Table 2). The body morphology of infants has also been shown to influence temporal-spatial (51) and kinematic characteristics of walking in toddlers, in particular maximum hip adduction in stance decreases in infants classed as 'slimmer' (52). The authors attributed these findings to lower inertia in the frontal plane of the thorax/head in more slim infants leading to less resistance against sideways movement. This body composition must also be seen as a limitation in data collection, with higher skin motion artefact expected due to increased subcutaneous fat, less stiff tissue and undeveloped bony prominences for palpation (53). The use of suits to reduce skin motion artefact and to overcome issues of placing markers directly onto sensitive infant skin has been implemented by Hallemans et al., (23, however this may likely amplify modelling error due to difficulties in marker positioning on anatomical locations. Additionally, due to the difficulties in recruiting and testing infants, studies involve small participant numbers and large numbers of variables (Table 2). Combining this with the anticipated high intra- and inter- individual variability leaves the existing studies underpowered and therefore a larger scale research study is warranted. Additionally, further work to understand the interactions between footwear and other extrinsic factors such as morphology, clothing and environment on gait development is needed.

Trunk kinematics and foot progression angles may also be of particular interest in terms of their maturation (22,54,55) and their influence on the foot during locomotion. Trunk oscillations in the sagittal and frontal planes during gait initiation have been shown to reduce with walking experience, reducing significantly from pre-walkers to those with 1-4 months walking experience (56). Considering differences within developmental groups, McCollum et al., defined three diverse kinematic approaches to walking based on patterns of trunk accelerations measured with inertial sensors (e.g. a "twister" infant uses high angular velocity

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of the trunk to facilitate progression) (55). These three approaches are not mutually exclusive, but can also overlap inter-individual and intra-individual of the same developmental stage. The authors suggest that the use of kinematic measurements, muscle activation patterns and the magnitude and direction of torques and shear forces on the walking surface would be able to distinguish these gait styles. Thus alluding to the loading of the foot plantar surface differing between these approaches. Bisi and Stagni used inertial sensors and defined a further style of walking (Pendulum), which became apparent one month after the onset of independent walking and increased in prevalence amongst infants as their walking matured until 6 months after walking onset (27). This technology overcomes some of the aforementioned limitations of using markers for 3D motion capture, and also enables the infant to move more freely. However inertial sensors have the potential for errors particularly at high velocities and in the frontal or transverse plane (57).

Few studies have collected EMG data on infants, which is not surprising given several methodological challenges. Increased thickness of subcutaneous fat, identification of underlying musculature and the design of equipment being for adult data collection (i.e. inappropriate inter-electrode distances) will all affect the quality of the data obtained from EMG equipment (58). Despite these issues, there are published data quantifying EMG in infants (Table 2). Okomota et al., (59) reported data spanning the development of gait by repeatedly testing one infant from neonate to 7 years of age. The transition from supported to unsupported walking in this individual demonstrated substantially longer tibialis anterior activity and co-contraction of the anterior/posterior musculature of the lower limb, both of which reduced after 3 months of independent walking experience (60). This was matched in a larger research study (N =8) at the onset of independent walking and 3 months later; co-contraction of the lower limb musculature was evident, alongside high variability between steps in individuals with low walking experience (26). Similarly, longitudinal changes in muscle recruitment strategies have been quantified in infants of 6 to 12 months of age, with reductions in agonist-antagonist coactivation (59,60).

The pattern of lateral gastrocnemius activation (in terms of probability of onset over the gait cycle) from early infancy appears to relatively closely replicate that of the more experienced independent walking and young adults (27,61). However, the probability of activation of the tibialis anterior in swing for pre-walkers and those with low walking experience for gait initiation was low (25-28%) compared with more walkers with at least 9 months experience (63%) (56). The maturation of the kinematic pattern of the ankle appears to mirror this

maturation of the tibialis anterior and gastrocnemius antagonist-agonist relationship. Mean curves of experienced independent walkers (≤3 years of age) portray dorsiflexion in swing, but reduced plantarflexion at toe-off therefore reduced plantarflexor moment and power generation compared to adults (48,49,61). Due to the developmental stages currently represented in literature, the difference between cruising, supported and independent walking is not currently evident in muscle activation patterns. We can infer that there is likely a further increase in organisation of muscle firing patterns to closer resemble those of more experienced, independent walkers. However, the different muscle recruitment patterns required for cruising sideways along furniture for example and their similarity to supported walking while facing forwards would be of interest. The consideration of sample size and the importance of appropriate EMG technology and data treatment would also aide the quality of ongoing work in this field.

Conclusions

It is evident that the measurement and quantification of the infant foot across the locomotor milestones is valuable. However, studies of younger children in the initial stages of walking has offered only limited information and there are gaps relating to how foot structure changes in response to the application of load during the development of standing and walking strategies. As described above, research studies relating to infant walking begin at weight-bearing as they are focused on the motor development of the infant and studies spanning the initiation of weight-bearing involve complex and challenging methodologies. Baseline data from periods prior to onset of weight bearing have not been reported and therefore any alterations to foot structure and function that maybe concurrent with the initiation of weight-bearing have not been quantified. This information is particularly important to enhance the knowledge base that underpins clinical assessment of infant development. Research must systematically select populations using precise developmental milestones for criteria, emphasise longitudinal research and recruit larger sample sizes than evident in current work. Additionally, considering the external validity of the study design in terms of locomotor strategy and the relevance of outcome variables are both key to obtaining meaningful results from infant participants. Overcoming these barriers is essential to increase our knowledge of the developing foot (and the lower limb) prior to experienced independent ambulation.

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Table 1 Published literature relating to plantar pressure data of infants.

	Bosch et al., 2010 (39)	Müller et al., 2012 (16)	Alvarez et al., 2008 (38)	Hallemans et al., 2003 (22)	Hallemans et al., 2006b (35)	Bertsch et al., 2004 (14)
Participants	36	157	10	7	10	42
Developmental stage	Recently started to walk freely	Able to walk unsupported	Age related only: 18 months.	Independent walking 0-2 months	Within a week of 2/3 independent steps	Able to walk several metres without support
Age	14.6±1.8 to 20.7±1.9 months	1 year age group	18.7±2.2 months	Not reported	Not reported	14.8±1.8 at first visit
Design	Longitudinal	Cross-sectional	Cross-sectional	Longitudinal	Longitudinal	Longitudinal
Measurement frequency and timing	Every 3 months for first year after walking onset.	Once, tested age ranges from 1-13 years.	Once, 15 age groups split every 3 months.	One participant 0,2,4,6 months after independent walking.	0,2,3,4,5,8,10,12,16,20 weeks after walking onset.	Every 3 months for 12 months following walking onset.
Data Collected	5 trials of each foot walking barefoot using Novel (4 sensors.cm^{-2}).	3-5 trials of right foot only using Novel (4 sensors.cm^{-2}).	3 walks for each foot using Tekscan (3.9 sensors.cm^{-2}).	8-24 steps per participant using RS Scan (3.5 sensors.cm^{-2}) calibrated with force plate.	One step per trial, usually 3-5 trials per session.	5 walking trials for each foot.
Regions	Total foot, hindfoot, midfoot, forefoot, hallux and toes.	Total foot, hindfoot, midfoot and forefoot.	Heel, lateral/medial midfoot, lateral/medial forefoot.	Heel, midfoot, lateral, central, medial metatarsal and hallux.		Heel, midfoot, forefoot, great toe and lateral toes.
Dynamic variables	Peak pressure, maximum force (%BW), contact area (% total foot contact), arch index. Median, 3rd, 97th percentile.	Contact area, plantar pressure and force time integral, arch index. Mean and 2 SD.	Average left and right feet. Force variables relating to relative timing in stance, relative distribution of maximum pressures across stance.	Peak pressures and relative impulse. Centre of pressure distance from line of progression in x and y.	Foot contact patterns (initial fore-foot contact, flat foot contact, and initial heel contact). COP Index (deviation from midline). Peak pressures and relative impulse.	Peak pressure, impulse, contact area, max F. Medial and lateral impulse and ratio. Normalised to body mass, whole contact area etc.
Outcomes	Results compared across 9 years. Age at walking onset did not effect parameters.		Results compared to other age groups (2-5 years and > 5 years).	Compared to adult data: infant data had pressure values magnitude of 25-50% of these.		

Please note that some literature has the data extracted for relevant ages only with the original papers representing a larger data set more varied in age. Where BW = body weight. Arch index = CAmid/ (CAfore+CAmid+CAhind); SD = standard deviation.

Table 2 Published literature relating to kinematics and electromyography data of infants

	Hallemans et al., 2005 (20)	Ivaneko et al., 2005 (51)	Chang et al., 2006 (23)	Okamoto et al., 2003 (55)	Dominici et al., 2007 (19)	Bisi and Stagni, 2015 (24)
Participants	10	7 (4)	8	1	12 and 6	20
Developmental stage	Low walking experience (< 6 months).	Early walking.	Able to walk 3-6 independent steps.	Outset at infant neonatal stepping response.	Independent walking 1 week, and 1.5-5 months walking onset.	First week of independent walking (5 consecutive steps without help).
Age	15.6±1.4 months	12-15 months of age	13.8±2.2 months	3 weeks – 7 years	12.9±1.2 and 17.4±1.1 months	13±1 months
Design	Cross-sectional	Cross-sectional	Longitudinal	Longitudinal	Cross-sectional	Longitudinal
Measurement frequency and timing	Once, 2 weeks- 5 months after walking onset.	7 participants independently walking, 4 participants 1.5 months prior to walking onset.	Walking onset then 3 months later.	From 3 weeks old 38 measures were taken to 7 years of age. 3 weeks – 3 years: measures 2 weeks to 2 months. 3-7 years: measures every 6 months.	Once for main study: One week of walking experience, 1.5-2 months after walking onset, 9-50 months after walking onset.	1, 2, 3 and 6 months following first session.
Walking speed and style	Self-selected	Walking without support, with hand contact and with trunk support	Self-selected from researcher to toys and parent at other end.	Not reported, not controlled. Walking was supported as required, at trunk, by hand progressing to none.	Collected- mean velocity of horizontal ASIS movement. Unsupported, semi-supported, supported.	Self- selected speed
Equipment	Markers: 14mm, Helen Hayes (inc body dimensions) attached to suit. Vicon (Mcam 460) 6 camera system operating at 250 Hz.	Markers: 14mm, Glenohumeral, ASIS, GT, lateral femoral epicondyle, lateral malleolus, fifth MPJ applied to skin. Vicon (612) camera system operating at 100 Hz. Electromyography RF, hamstring, soleus-gastrocnemius and TA. BTS and Delsys at 1000Hz.	Markers: tempero-mandibular joint, shoulder, elbow, greater troch, femoral condyle, mid shank, heel, 3rd MPJ on left leg only. GaitRite Electromyography: TA, GAS, RF, BF	Electromyography of biceps femoris, gluteus maximus, lateral gartrocnemius, rectus femoris, tibialis anterior and vastus medialis. 15 mm inter-electrode distance. Video camera (60 Hz) to detect stance versus swing.	Markers (14 mm): glenohumeral joint, ASIS, greater trochanter, lateral femoral epicondyle, lateral malleolus, 5th MPJ (on a 1cm stem). GRF	Inertial sensors on lower back and right leg, recording acceleration and angular velocity at 128 Hz.
Data Collected	3-5 trials (gait cycles).	≈10 trials walking with hand contact, with trunk support	Usable 3-6 strides per toddler for visit 1 then 5-8 for visit +3 months.	Repeated steps. Not defined or reported.	10 trials of ≤3 mins (depending on endurance).	10 consecutive strides, excluded first and last strides.
Variables	28 kinematic and kinetic variables. Spatiotemporal scaled to body size. Net joint moments and powers scaled to leg length. Magnitude at maximums and minimums compared once normalised to gait cycle.	Intersegmental coordination. Foot trajectory. 5MPJ marker vertical dis swing. Trunk oscillations: SW and SL normalised limb length. Single limb support normalised ST.	Normalised step length, step width by leg length. EMG: Sum of on/off, State analysis (combination of on and off for each frame), Probability of activation, Co-activation. Coefficient of variation calculated to define variability	General EMG patterns of stance and swing, reciprocal patterns, co-contraction patterns and reversed reciprocal patterns.	Intersegmental coordination. Foot trajectory. 5MPJ marker vertical displacement swing. Trunk oscillations Step width and step length normalised to limb length. Single limb support normalised to stance time.	Gait strategies (based on previous work). Stride time, swing time, stance time, cadence, acceleration, regularity.
Outcomes	Comparison to standard adult patterns.	Compared to adult data. Influence of support on postural stability and gait and the kinematic patterns of walking.	Compared to adult.	Developmental changes in posture reflecting strength increases and improvements in balance.	Control of foot trajectory changes over time and support condition.	

Please note that some literature has the data extracted for relevant ages only with the original papers representing a larger data set more varied in age. Where RF = rectus femoris, TA = tibialis anterior, GAS = gastrocnemius, BF = biceps femoris.