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Ground Reaction Forces during the Biomechanical Gait Analysis in Children

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***Abstract*—*The objective of this article was to review the aspects related to the biomechanical variables that influence human gait and to understand how the ground reaction forces act during the process of ambulation. The research was made through Scopus and Google Scholar database and the key words used were: "gait", "children", "walk" and "ground reaction forces". Gait evaluation is used in many fieldsto make diagnoses, recommend interventions and monitor their effect. Muscle recruitment, immature stride dynamics a nd, strategies of equilibrium control, immature sensory integration during stance, are some of various biomechanical and neural factors related to the kinetic pattern of walking in children. There are different biomechanical parameters and methodologies applied to analyze the gait pattern in children, and severalstudies have addressed medical treatments and their influence in the gait parameters. Therefore, the study of the relationshipbetween biomechanical variables and the gait maturity of the children is important to the development of new treatments and interventions in this population.*

***Keywords*—biomechanics,childhood,force platform, kinetic, walking.**

I. INTRODUCTION

Gait is a unique and fundamental movement of the individual, considering that two people do not move in an identical way. During the walk one of the feet is always in contact with the ground and, for a moment, both feet touch the ground, for this reason walking is an alternating sequence of single and double support of the feet with the floor. Periodicity of gait is supported by two basic requisites: periodic movement and ground reaction forces to support the body, which characterizes the gait cycle. Thus, gait descriptions, in general, refer to what happens in the course of only one cycle, assuming that successive cycles are all equal [1].

The gait cycle is initiated from the foot contact on the ground, usually done with the heel, starting the stance phase, which is divided into first double support, single limb stance and second double support. The first double support is characterized by the initial contact. The single limb stance, on the other hand, is divided in loading response, midstance and terminal stance. The second double support is characterized by the beginning of the next gait phase, the swing phase. The swing phase is characterized by the initial swing, midswing and terminal swing. The end of the gait cycle occurs when the same foot again comes into contact with the ground [2].

Fundamental motor skills, such as walking and running, are intimately linked to factors such as biological maturation, growth and life experiences [3]. The human gait is the result of a complex interaction of muscular forces, joint movements, and neural motor commands. In the last century, many variables that characterize human gait have been identified and quantified. These include ground reaction forces, muscle activity, limb movement, energy-metabolic cost and others [4].

Although the purpose of gait is the forward movement, upper limb movements will occur to maintain displacement of the center of mass of the head, trunk and upper limbs with a low amplitude and symmetrical coordination in the vertical and lateral directions [4]. The beginning of the walking process is considered the main challenge to overcome by children in the motor development phase. The upright position in babies is found around 1 year old. At this age, they are able to perform the first steps independently. The pattern of walking at this stage is continually challenged by the characteristics of the gravitational field, in addition to being influenced by the lack of muscle strength, by difficulties in balance and control [5].

Kinematic analysis and electromyography measurements of the gait require time-consuming procedures for attaching markers and skin electrodes to the body of the subject. On the other hand, the evaluation of the ground reaction force-time curves acquired with force plates has a considerable advantage of the possibility of immediate visual inspection of a measured test and is a relatively simple method that allows

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obtaining the magnitudes of the reaction forces that act in the human body.

The purpose of this study was to review the literature related to the kinetic evaluation of the children gait through the ground reaction forces (GRF) measurement. Firstly, the article describes the normal gait and its characteristics in children. Secondly, we review the aspects related to the GRF and force platforms. Then, we review some evidence about kinetic parameters. The article concludes with a discussion of the literature and clinical applications for biomedical engineering.

II. METHODS

The research was carried out in the following electronic databases: Scopus and Google Scholar. The search included articles published in English and Portuguese with no period limitation. The descriptors used were: "gait", "children", "walk" and "ground reaction forces". After reading the abstracts of the articles, we selected the papers that used force platforms for gait analysis and evaluated the ground reaction forces, as showed in Fig. 1.

In addition to the use of academic articles that presented the purpose of the study of the gait of children with the help of force platforms, we also included in this article books related to gait analysis, dissertations and thesis that were related to the gait of healthy children or children with an abnormal gait.

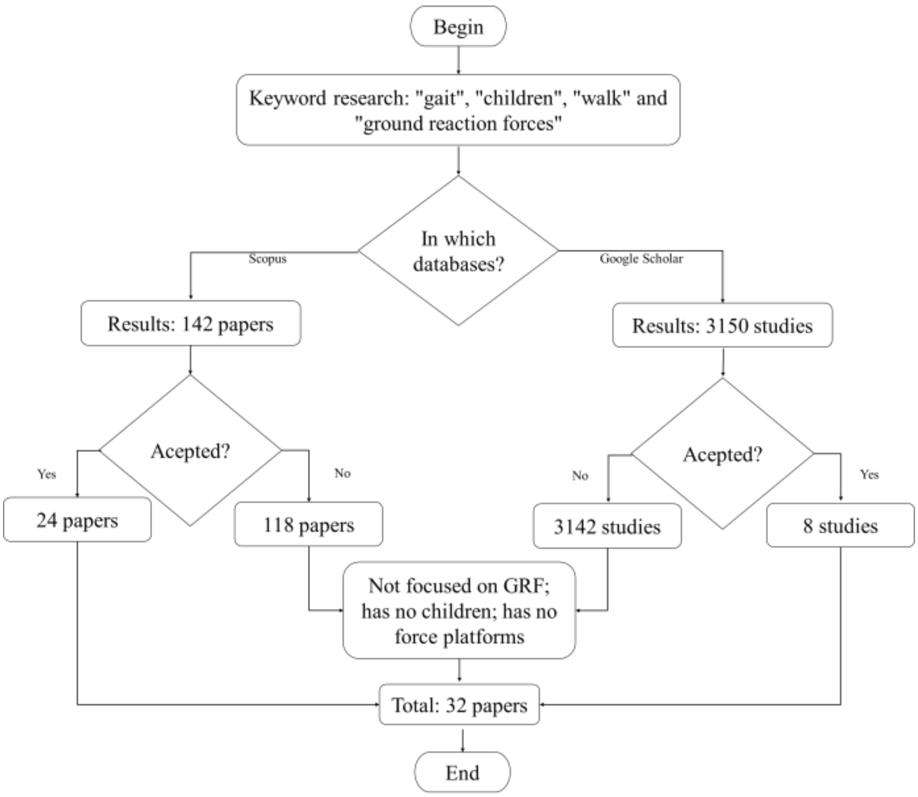

Fig. 1: Flowchart of the search and selection process.

III. RESULTS

3.1 Characterization of gait

The human gait is the result of a sequence of events, initially occurs through the command from the central nervous system and then withthe transmission to the peripheral nervous system. After this stage, the muscles that will develop tension will be contracted and will happen the generation ofmomentsand forces on the joints, resulting in the regulation of the forces and torques in the skeletal system, generating the displacement of the segments and the production of forces that lead to movement [6].

Following the international convention, gait analysis laboratories characterize the trajectory followed by the right lower limb, in two distinct phases, supporting phase and oscillation phase (also known as balance sheet phase) [7]. Fig.2(adapted)shows a summary of the running cycle[2].

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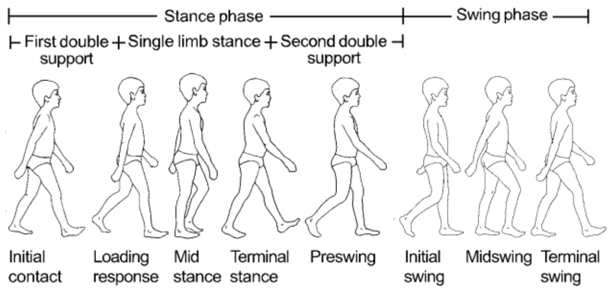

Fig. 2: Gait cycle.

It is possible to define the support phase as the period in which the foot is in contact with the ground and can be subdivided into first double support from0% to 12%, simple support from12% to 50%, and second double support from50% to 62%. The first double support is characterized by the initial contact. The single limb stance, on the other hand, is divided in loading response, midstance and terminal stance. The second double support is characterized by the pre-swing and the start of the next gait phase, the swing phase. Thus, the swing phase is characterized as the period where the limb is in progression movement and without presenting contact with the ground. It is subdivided in initial swing, midswing and terminal swing phase[8].

During the process of normal locomotion, the human body is erect and in movement, performing alternate movements of support phase and swing between the lower limbs. As the body moves to the supporting leg, the other leg will be projected forward in preparation for the next support phase. One of the feet will always be on the ground during the period when the support is transferred from the supporting leg to the advancing leg; there will be a brief moment when both feet will be in contact with the ground. As the individual walks faster, this double footing condition will occurin smaller fractions of time [1].

3.2 Force platforms

One of the instruments used the kinetic analysis of the gait is the force platforms. Basically, the force platform will be composed of two rigid surfaces, one upper and one lower, interconnected by force sensors [9].

Regarding the configuration of the construction of the force platforms, they can be made basically with the application of strain gauges for the instrumentation of the transducers or with the application of piezoelectric materials.

The strain gauge or resistive extensometer is a sensor that provides deformation measurement. It consists of a set of wire or metal strips in the configuration of a serpentine, always presenting the least space between the wires or the blades in order to reduce shear stresses [10]. The materials used to make these sensors should have the following characteristics: high sensitivity, good weldability, corrosion resistance and high resistivity as well, as high flow stress, low hysteresis and low sensitivity to variations thermal [10].

The strain gauges sensors, when subjected to the action of a force, will determine the mechanical deformation of a structure with the variation of the electric resistance, which will be proportional to the applied force. However, the piezoelectric materials will be able to produce alternating electrical voltages at the moment of alternating tensile or compressive stress [11].

It is important to point out that piezoelectric materials will present higher cost when compared to strain gauges, but they have many advantages such as repeatability, linearity, high frequency and low hysteresis [11].

Regarding the positioning of the sensors, three types of platforms should be highlighted: with a single sensor in the center of the platform, with a triangular distribution of the sensors inthe three corners and with a rectangular distribution (sensors distributed in the four corners of the platform).

Currently, there are several options of commercial force platforms, for example the Bertecforce plate(Fig.3). Among the models of the company cited, one that is employed for both clinical analysis and research related to human gait is the model 4060-08[12].


Fig. 3: Bertec force platform.

With regards to platforms that use piezoelectric sensors, it is possible to cite the model Type 9285BA, from the company Kistler (Fig.4). In this case, it will be possible to determine the measurements of the GRF, as well as the recording of the contact areas[13].

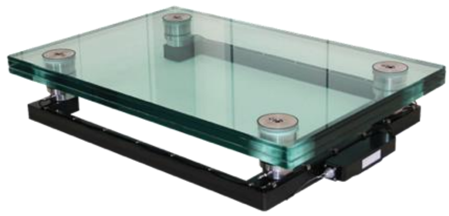
Fig. 4: Kistler force platform.

Another platform is that from the BTS Bioengineering, INFINIT-T P6000 (Fig.5), which features spherical head sensors that provide a homogenous distribution at the points of contact[14].

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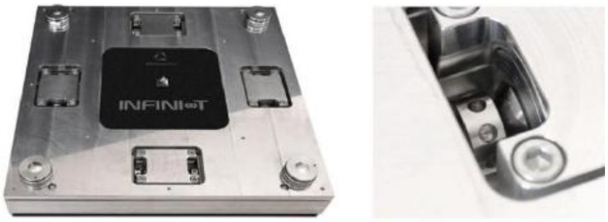

Fig. 5: BTS Bioengineering force platform.

3.3 Noise

With regard to data collection related to gait analysis on force platforms, a major problem that must be addressed is noise elimination. Noise can be define as an unwanted signal that will impact the communication, perception or processing of a signal [15].

To reduce the noise problems we can apply filters during the signal processing. Oneexample of a filter used is the low-pass filter, considering that the cutoff frequencies of these tests will be at most 50 Hz. This filter will allow the passage of low frequencies and will reduce the amplitude of the frequencies greater than the cutoff frequency.

One example of filter used in ground reaction forces analysis during the children is a method applied [16], the estudged the balance and symmetry of gait in children with cerebral palsy. Using two force platforms, with a sampling frequency of 960 Hz, the gait of 18 children was analyzed. In this study, the data were filtered using a low-order fifth-order filter with a cutoff frequency of 10 Hz.

In order to analyze the gait of 40 children with Autism Spectrum Disorder [17],were used two force platforms in their essays. A low-pass filter with a cutoff frequency of 30 Hz was used to treat the noise in the ambulation processes. In this study the researchers used a sampling frequency of 1000 Hz.

In a project that performed the comparative analysis of the forces in the gait of 30 deaf children and listeners [18], were used two force platforms to evaluate children's walking, with a sampling frequency of 1000 Hz. In order to filter the signal, a low-pass filter of fourth order, with a cutoff frequency of 20 Hz was applied.

3.4 Ground reaction forces

Ground reaction forces can be known through Newton's third law, which stands out for being equal, but meaningful inverse to the forces that gave rise to it. During the gaitof a child, some forces acting on this process will be observed: the force exerted by the body on the ground, as a result of the action of gravity and the ground reaction forces, which will be the surface support reaction [19].

A challenge for the study of ground reaction forces is to decompose them into left and right profiles, considering that there will be two consecutive steps with the feet on separate force platforms. Usually, the individual who will be performing the gait will use visual guidance to correct their route and reach the platforms correctly, which may affect the trials and impact on the step length variability. One way of correcting this type of problem will be to carry out several tests according to the need, but one must be aware of a high number of repetitions, considering that the excess of these can result in fatigue and alter the gait pattern [20].

Among the variables most frequently evaluated in studies on gait biomechanics, we can mention the ground reaction forces on the Z axis (vertical component), ground reaction forces on the Y-axis (anterior-posterior) divided inbraking and propulsive phases. On the other hand, ground reaction forces on the X-axis (middle-lateral) are less frequently used due to relatively high [21].

Fig.6 shows a vertical ground reaction forces curve, where it is possible to evaluate the first peak (F1 - initial contact of the foot with the ground), the valley that is between the first and second peak (F2 - medium support phase), as well as the second peak (F3 - pre-swing phase) [5].

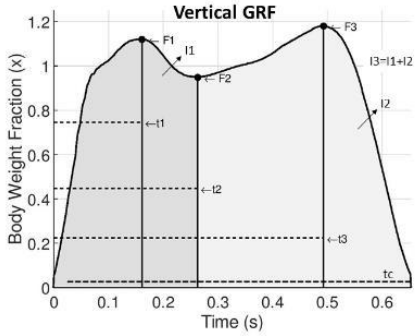

Fig. 6: Ground reaction forces on the Z axis.

The first peak F1 represents the force that will occur in the instant we have the impact of the heel on the ground. This force will vary between 110% and 120% of the individual's body weight during a normal gait [22].

It should be noted that the valley between the first peak F1 and the second peak F3 is related to the moment when the foot is flat on the ground and the strength recorded will be approximately 80% of the body weight of the individual [22].

The peak F3 will be referring to the force necessary to separate the foot from the ground, allowing it to continue advancing. This force will be similar to the force recorded at the FZ1 peak, varying from 110% to 120% of the individual's body weight during a normal gait[22].

The anterior-posterior forces, measured in Y-axis direction of the movement are shown on Fig.7. We can

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notice the heel moment (F4-braking) and the propulsion phase (F5-maximum strength) [5].

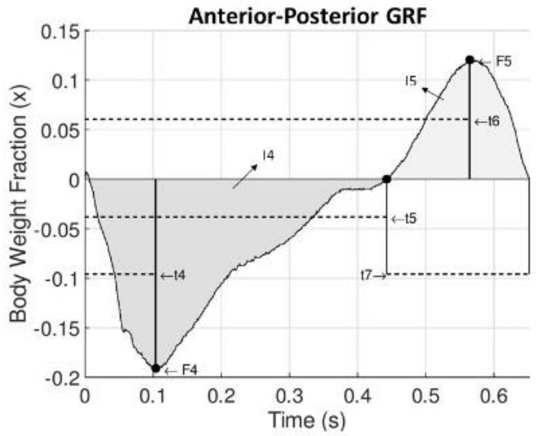

Fig. 7: Anterior-posterior ground reaction forces curve.

The force marked as F4 corresponds to the braking force, which represents the force exerted by the heel in the direction of the gait. Peak F5 is related to the force generated by the anterior foot in the opposite direction of the gait, representing the propulsive force [22].

It should be noted that the values of the braking and propulsion forces will register values close to 20% of the total body weight of the individual [22].

3.5 Biomechanics of gait in children

During the process of gait maturation, we can observe that at the beginning of the child's walking, each step tends to be independent of the following one. The child gives small steps with a small extension of knees and hip. During this maturation phase childrenwill step with flat feet and pointing out your toes. Individuals at this stage will have the habit of putting their feet well apart from each other to improve their lateral balance [23].

When analyzing the mechanisms of locomotion of a child, it can be observed that theywill occur in the supraspinal centers and will involve the conversion of a desire for movement in a pattern of muscular activity, necessary for the execution of the gait process (Fig. 8,adapted)[2].

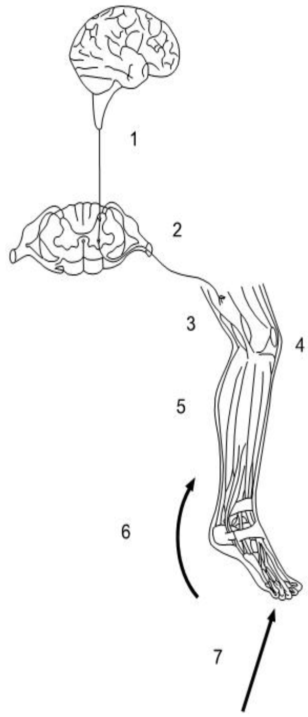

Fig. 8: Seven components that form the basis of gait.

The gait process presents seven distinct events, as shown in Fig. 8: (1) recording and activation of the gait command in the central nervous system, (2) transmission of gait signals to the peripheral nervous system, (3) (4) generation of forces and moments in the synovial joints, (5) regularization of the forces and moments applied in the joints by the anthropometry of the rigid segments, (6) displacement of the segments in such a way that they are recognized as functional gait, (7) generation of ground reaction forces. This model, called cause and effect, will presentgait as a process of neural coordination and collaboration of the nervous and musculoskeletal systems, in order to achieve a correct dynamics, with the maintenance of body balance in a small support base [24].

When the child reaches two years of life it is possible to observe during running the aerial phase (moment of absence of both feet), characteristic of this initial stage of development. However, in the development of the 4th and 5th year of life, one can perceive greater control and coordination of fundamental movements, even though the notion of space and time is still in development [25].

IV. DISCUSSION AND CONCLUSIONS

Gait evaluation is used in many fieldsto make diagnoses, recommend interventions and monitor their effect. In most cases, the clinical method will be limited to visual observation of the patient's gait. However, the observational analysis of gait has questionable validity. Quantitative analyzes with kinetic measurements showed higher reliability since they will be based on the analysis of the ground reaction forces [26].

Various methods were used to investigate gait biomechanical models in children asthe study [27],which points out in a systematic review that evaluated the effects of shoes on walking and running gait, compared to barefoot in healthy children.

One of the clinical aspects of interest is the evaluation of the dynamic balance during gait. With regard to the development of a child's balance system, it should be noted that it presents postural control techniques similar to adults as it approaches 7 to 8 years of age. At ages below 7 and 8 years, the child presents incomplete development of the vestibular and nervous system integration, which affects their static and dynamic posture [28].

It is through the posture that the individual has the control of the beginning of the movementand can maintain the continuation of the gait. Another fundamental aspect in which the posture will contribute will be in the realization of precise movements. In some studies it is possible to verify a relationship between gait symmetry and cadence in pre-school children [28].

In astudy carried out with children with Autism Spectrum Disorder, one of the most important parameters to analyze the neurological function wasthe symmetry of gait. In healthy gait, minimal asymmetries are observed and in pathological gait exaggerated asymmetries are observed [29].

Some studies have used gait analysis as a tool for decision-making in medical procedures in children with spina bifida. They have evaluated excessive hip flexion and femoral rotation through kinetic and kinematic gait analyzes in children with this disease [30]. The authors emphasize the importance of the use of quantitative data of gait analysis for clinical evaluation and surgical recommendation.

In young children, walking is influenced mainly by age and walking speed. In this way, it is possible to perceive the importance of correlating temporal parameters such as average speed, maximum speed and cadence with gait maturity [31].

Among the variables that will be influenced by speed, we can highlight the increase in stride length, reduction of cycle length and duration of the support phase as speed increases [4].

Another important aspect is thetime required for a walking cycle that is approximately 1.03 seconds as well asthe number of steps per minute that varies from 90 to 120 steps. Also, the speed during comfortable walking is around 1.25 meters per second. On the other hand, the mean distance between the two feet (width of the stride) is 8 cm, with the foot presenting an angle of 6.7 ° [32].

In another study [33] the following temporary time parameters were measured for healthy boys and girls of the same age group,when studying gait characteristics of the subjects with a mean age of 6,8 years, who presented crooked feet and underwent surgery. They found a running speed of 1.02 m / s ± 0.18; cadence of 136.36 steps / min ± 32.38; pass time of 0.92 s ± 0.20 and stride length of 0.91 m ± 0.05. The authors observed that gait parameters of children who underwent surgery presented abnormal patterns when compared to gait parameters in healthy children, since operated children tended to compensate for foot and ankle abnormalities by altering gait. The researchers believe that changes from the support stage of the crooked foot may alter the swing phases of the normal side, as well as changes in the range of motion.

In a project that conducted the comparative analysis of the gait of children with and without flat feet, Chen et al. [34]described the percentages of duration of the support and swing phases of healthy children agedfrom 5 to 11 years: 59.1% for support phase (barefoot gait) and 40.9% for swing phase (gait was performed barefoot). In this study, the authors were able to perceive that the gait of children with flat feet is characterized by a greater range of motion, lower vertical force in the first and second peak (FZ1 and FZ2) and longer duration of ground reaction forces when compared the gait of healthy children.

In another study [35], an analysis of patients with hemophilia was performed in a sample of 42 patients aged 4 to 18 years. It was found that the walking speed of the young with moderate hemophilia was 1.22±0.15 m/s and the support and swing phase percentages were respectively 56.4% and 43.6%.

The speed of displacement influences the vertical acceleration, because decreasing the speed, momentum and the vertical acceleration will also decrease impacting both force peaks and valley resulting in values close to body weight and the absence of peaks. Differently from what happens in the cases of speed reduction, when the speed of gait increase, it will be possible to perceive the increase of the force peaks, as well as the reduction of the existing valley[36].

Two important variables that will impact the analysis of the gait are the vertical braking impulse and the vertical propulsion impulse. The vertical braking impulse is calculated by integrating the areabelow the vertical ground reaction force curve from the start of the stance phase with its final limit at point F2 (mid stance phase), as shown in Fig.6. The vertical propulsion impulse is calculated through of the integration of the area below the vertical ground reaction force curve from F2 until the end of the stance phase (which will be after F3- second force peak, when the ground reaction forces are equal to zero again)[37].

When analyzing the gait of a group of children aged from 5 to 11 years, with and without flat feet [34], were measured the vertical ground reaction forces and its respective times. In this study it can be seen that for healthy children the first vertical force peak (FZ1) was 115.66±9.20% (normalized strength value, expressed as a percentage of children's body weight) with time in FZ1 (TZ1) of 20.9±2.20% (time expressed as a percentage of the support time).

Regarding the second vertical force peak (FZ2) of the previous study [34], researchers reported that it was 104.20±7.90% (normalized strength value, expressed as a percentage of children's body weight), with time in FZ2 (TZ2) of 77.20±4.70% (time expressed as a percentage of the support time). It should be noted that between the two peaks was presented a valley with a minimum value of force (FZ0) of 72.20±10.80% (normalized force value, expressed as a percentage of children's body weight), with time in FZ0 (TZ0) of 48.80±7.00% (time expressed as a percentage of the support time).

In a study that analyzed the progression of children with an autism spectrum disorder [17], investigated the ground reaction forces of 15 children with autism spectrum disorders and 25 children with typical development aged from 4.3 to 12.4 years. In this study the researchers measured the ground reaction forces in the vertical of healthy children and found that the first vertical force peak (FZ1) was 109.86 ± 10.90 (normalized force value, expressed as percentage of weight of children) with time in FZ1 (TZ1) of 23.20±2.70% (time expressed as percentage of support time). Regarding the strength of the second peak (FZ2), the researchers reported that it remained at 109.51±6.92%, with time in FZ2 (TZ2) of 77.96±2.83% (time expressed as a percentage of the support time). On the other hand, the value between the two peaks (FZ0) presented a force of 78.95±7.22%, with time in FZ0 (TZ0) of 44, 98±5.53%.

In another study[38], children up to 5 years of age were observed. The most important finding in this study was that about 24 months of age the ground reaction forcesare similar to the adult pattern. They noticed that between the age of 2 and 3 years it is possible to notice a significant increase in the development of the heel strike, from the beginning to the complete development of the walking pattern, confirming that the study of ground reaction forces is appropriated for the analysis of children's gait and also to detect abnormalities that can be related to neurological disease.

Muscle recruitment, immature stride dynamics, and strategies of equilibrium control, immature sensory integration during stance, are some of various biomechanical and neural factors related to the kinetic pattern of walking in children. For this reason, a study [39] was carried out in order to identify the age differences in kinematic and kinetic gait parameters between the ages of 3 and 13 years. The authors suggested that in general children present gait kinetics similar to adults by the age of five years, which can be related to differences in the ankle joint moments.

After the analysis of several gait-related studies, it is possible to understand the importance of gait biomechanical parameters for the development of human locomotion and how it is related to the gait level's maturation.

Several studies have highlighted the need to analyze variables such as cadence, speed, support phase, swing phase, body weight distribution as well as the importance of studying the ground reaction forces, through analysis of the anterior-posterior components, mid-lateral, and a vertical component.

The cited studies have presented different biomechanical parameters with different diseases that can affect children in distinct age groups. Some studies have addressed medical treatments and analyzed their performance through gait parameters.

Through the analysis that some authors have performed with the gait variables, such as gait speed and cadence, with the maturity of the studied individuals, we can prospect the development of new studies that will investigate parameters that can impact on the maturity of the human gait like braking, propulsion, speed and distribution of body weight.

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