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Ground reaction force and support moment in typical and flat-feet children

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1. Introduction

Flat-foot is one of the most common foot deformities in children that may lead to foot or ankle pain during walking. A flatfoot deformity is where the arch on the inside border of the foot is more flat than normal and the entire sole of the foot comes into complete or near-complete contact with the ground [1]. The deformity can occur in all age groups, but appears most commonly in children. It should be treated with foot orthosis, exercises or surgical treatment. Lack of an appropriate treatment may trigger additional complications including joint deformity, back pain, and gait instability [2-5]. Various techniques were reported to assess the arch height including radiographic measurements and footprint analysis, which are the most commonly used methods [6-8]. Ground reaction force (GRF) during gait can provide insight into the functional manifestations of foot and ankle disorders and may be used for early diagnostic of abnormal foot biomechanics due to flat-foot. Several studies [3, 9, 10] have explored GRF during gait for various foot complication in adults, but to date still little is known about the ground reaction force of children with flat-feet. Examining the GRF is of key importance to assess abnormal foot loading due to a flat-foot disorder. Additional, supporting one's body weight during the stance phase of gait is an important subtask for children [11-13]. The stance phase of gait requires several capabilities such as balance, muscular coordination, strength and mobility of the lower limbs. The concept of the support moment has been used to determining the relative contribution of the lower extremity joint moments to prevent collapse. Kepple developed a method to calculate the relative contributions of the lower extremity joint moments to forward progress and support during gait [14]. They found that the ankle plantar flexors with a significant assist from the knee extensors produced forward progression. In static standing, an ankle strategy, hip strategy and combined strategy were used to maintain the balance of the human body [15]. However, the postural recovery mechanism based on the support moment in pathologic gait has not yet been clearly defined.

The purpose of the study was to explore abnormal foot loading associated with the flat-foot deformity. Specifically, we compared the ground reaction force and the support moment between a group of flat-foot children and an age-matched control group.

2. Testing procedures

The evaluation was carried out on 60 symptomatic flexible flat-foot (51.7% girls) children between the ages of 6-16 years and 25 (40% girls) age-matched children as a control group. Both patients and control subjects were randomly selected from a total population of 250 primary schoolchildren. The local ethics committee approved the study. All parents/legal guardians received full information about the study before giving signed consent. All subjects were screened with a detailed medical history and were not being treated for any systemic disease. Clinical diagnosis of flat feet was based on observation of ankle dorsiflexion and plantarflexion, rearfoot, midfoot, and forefoot ranges of motion in triplane. Gait observation was conducted with the child barefoot. Inclusion criteria were: age range 6-16, arch height of bilateral feet, skin condition, knee and hip position, and body symmetry. Exclusion criteria were any other disorders different than flat-foot that may impact the subject's gait, ground reaction force, or joint's moment. The natural gait pattern was assessed in the sagittal plane of movement. Reflective markers were placed on the body according to the Oxford model as shown in Fig. 1 [16].

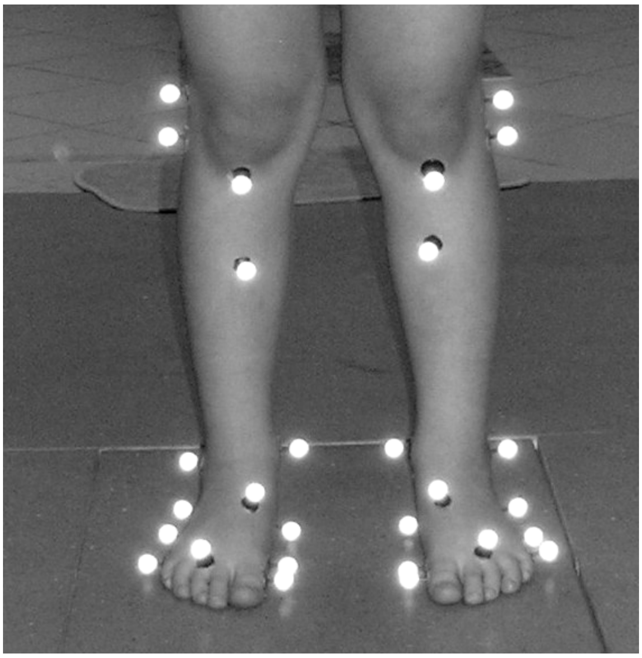

Fig. 1 The position of the markers on the body

The kinematic data were obtained with an opto-electronic system (Motion Analysis System) while three AMTI force platforms embedded in a 12 m walkway were used to obtain the ground reaction forces. The time-distance parameters were determined by foot-contacts or were defined during the digitizing process. Motion of all the foot segments was described with dynamic equilibrium equations [17, 18].

The force data were sampled at a rate of 1000 Hz. Each test was repeated to gather at least five trials while the subject walked at their habitual speed. The GRFs were quantified by three vectors in the vertical (*Fz*), anterior-posterior (*Fx*) and medial-lateral (*Fy*) planes. Fig. 2 represents a typical pattern of ground reaction force. The vertical force can be characterized by a double bump pattern. The first is related to body weight loading and the second one is due to push off. The vertical ground reaction force (*Fz*) was characterized by Fz_1 (maximum force within first 50% of stance phase), Fz_2 (maximum within the second 50% of stance phase) and Fz_0 (the minimum value between opposite foot off and foot contact). The anterior-posterior ground reaction (*Fx*) was characterized by Fx_1 (maximum posteriorly directed force), Fx_0 (minimum posteriorly directed force), and Fx_2 (maximum anteriorly directed force). The mediolateral force *Fy* was characterized by Fy_1 (maximum lateral force), Fy_0 (minimum lateral force), and Fy_2 (maximal medial force) [11-12]. The forces were normalized to the body mass, N/kg.

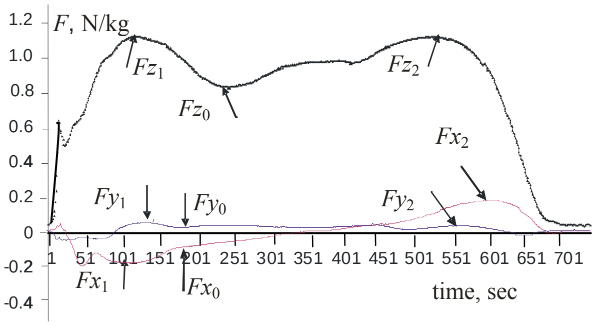

Fig. 2 A reprentative pediatric flat-foot ground reaction force

The lower limb joint moments were determined by using Newton-Euler equations [11, 12]

$$\vec{M}_i = \vec{F}_i r_i \qquad (1)$$

where $\vec{M}_i$ is moment in the *i*-joint of the lower limb, Nm/kg; $\vec{F}_i$ is force in the *i*-joint of the lower limb. N/kg; *r* is the perpendicular distance, m.

The joint moment at the hip, knee and ankle were computed using an inverse dynamic approach, and then the support moment and the contributions to the support moment were calculated using Eqs. 2 and 3 respectively

$$\vec{M}_s = \vec{M}_H + \vec{M}_K + \vec{M}_A \qquad (2)$$

where $\vec{M}_s$ is support moment, Nm/kg; $\vec{M}_H$ is hip moment during the stance phase, Nm/kg; $\vec{M}_K$ is knee moment during the stance phase, Nm/kg; $\vec{M}_A$ is ankle moment during the stance phase, Nm/kg.

The support moment was defined as the sum of all joint moments in the lower extremity [11, 12]. By its definition, positive values were regarded as extensor moments which prevent collapse and negative values as flexor moments which facilitate collapse. For determining the joint's participation in the support moment the area under the curve of suport moment for the hip joint, for the knee joint, and for the ankle joint was calculated as below

$$\int_{t_1}^{t_2} M_S(t)dt = \int_{t_1}^{t_2} M_H(t)dt + \int_{t_1}^{t_2} M_K(t)dt + \int_{t_1}^{t_2} M_A(t)dt \quad (3)$$

where t_1, t_2 are the time of signal duration, s; M_s is support moment, Nm/kg; M_H is hip moment during the stance phase, Nm/kg; M_K is knee moment during the stance phase, Nm/kg; M_A is ankle moment during the stance phase, Nm/kg.

Means and standard deviations were calculated for the total subject sample for the data from the force platforms. Computer software Statistica 8.0 (StatSoft, Tulsa, OK, USA) was used for computations.

3. Results

Results showed that the flat feet subjects walked at a natural speed of (1.18± 0.12) m/s, whereas the control subjects walked at (1.23± 0.14) m/s. Results from the ground reaction force suggested that for flat feet subjects the maximum force amplitude during the stance phase (Fz_1: the first peak) occurred significantly sooner than for typical subjects on average by 7% (for flat-feet subjects 110 msec from the unset of stance initiation vs. 120 msec for control subjects, $p < 0.05$). However, no significant difference was observed for the second peak (Fz_2). Force absorption causes an amplitude reduction for the second peak compared to the first one for both flat-feet and control subjects (average reduction values was 0.8%, $p > 0.5$). In the anterior-posterior plane, the amplitude of the force in the posterior direction (Fx_1) was significantly lower for the flat-feet group (0.19 ± 0.05 N vs. 0.22 ± 0.06 N, $p < 0.05$). However, no significant difference was observed for the amplitude of the force in anterior direction (Fx_2) as well as medial (Fy_2) and lateral (Fy_1) direction, $p > 0.05$.

Table 1

The ground reaction force summary measures for the control and flat feet groups (±SD)

GRF	Control children	Flat-feet children
Fz_1	1.258±0.142	1.027±0.125
Fz_0	0.809±0.095	0.822±0.075
Fz_2	1.082±0.090	0.995±0.087
Fx_1	0.551±0.065	0.548±0.074
Fx_0	-0.223±0.043	-0.191±0.052
Fx_2	0.186±0.064	0.181±0.035
Fy_1	0.082±0.034	0.069±0.022
Fy_0	0.0310±0.018	0.0312±0.011
Fy_2	0.061±0.024	0.054±0.026

Fig. 3 presents the support moment of each joint for the stance phase normalized to 100%.

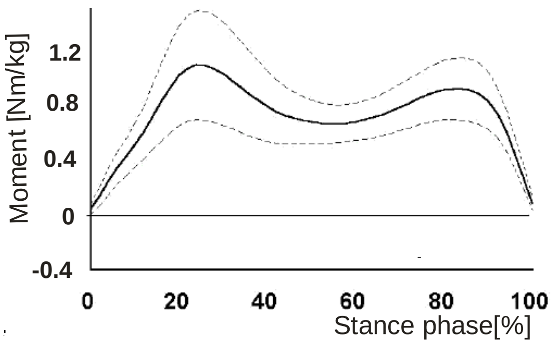

Fig. 3 The support moment for flat feet children

It was found, that the curve of ground reaction force is very similar to the curve of the support moment. The high correlation for the two curves was observed ($r > 0.9$). Table 2 presents the average value of the area under the support moment curve for the hip joint, the knee joint, and the ankle joint for the control and flat feet subjects.

Table 2

The average value of the area under the support moment curve for all joints of lower limbs (±SD)

Lower limb joints	Control subjects	Flat-feet subjects
Hip	0.064±0.014	0.049±0.095
Knee	0.061±0.027	0.055±0.029
Ankle	0.175±0.031	0.207±0.037

For the control and flat feet subjects the ankle joint moment plays the most important role to support the whole body (58.3% for control subjects vs. 66.6% for flat feet subjects). The hip joint (21.3% for control subjects vs. 15.6% for flat feet subjects) and the knee joint (20.3% for control subjects vs. 17.7% in flat feet subjects) contribution to the support moment was lower in the flat-feet group.

4. Conclusions

Despite some investigations in the area of GRF in adults with foot complication, still little is known about the GRF in children suffering from flat-feet complications. In this study, we explored the difference in GRF between flat-feet children and aged-matched control subjects. Few studies have examined the three-dimensional trajectory of GRF during walking in flat-feet children. Bertani et.al [3] studied 20 children (aged between 9-14 years) with idiopathic flat-foot. They found significant abnormal GRF parameters during the terminal stance phase. They suggest that children with flat-feet tend to walk with a reduced compliance in the loading response phase due to the impaired function of the hindfoot. Although we observed that the peak of the vertical force appeared earlier in flat-feet children than control subjects, we didn't observe any significant difference between the magnitude of the force in the vertical direction as well as medial-lateral and anterior directions. However, the amplitude of the force in posterior direction was significantly lower in flat-feet children compared to the control subjects. These results have shown that the support moment could be used to assess the weight bearing strategy during gait of flat feet and normal subjects. The strategy was remarkably consistent from one control subject to another when the subjects walked at their natural speed. These findings agreed with those reported by Winter [11, 12]. This study which analyzed the relative contributions of the lower limb joint moments to body support will be helpful to understand many unexpected walking and compensatory mechanisms for various pathological gaits.

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PLOKŠČIAPĖDŽIŲ IR NEPLOKŠČIAPĖDŽIŲ VAIKŲ ŽEMĖS REAKCIJOS JĖGA IR ATRAMOS MOMENTAS

R e z i u m ė

Žemės reakcijos jėgos įvertinimas gali suteikti vertingos informacijos, kai reikia parinkti tinkamą avalynę plokščiapėdžiams vaikams, siekiant sumažinti plokščiapėdystės pasekmes ir kartu apriboti tolesnes komplikacijas. Pagrindinis šio tyrimo tikslas – ištyrinėti vaikų dinaminį pado apkrovimą einant. Tyrime dalyvavo 60 plokščiapėdžių vaikų ir 25 to paties amžiaus kontroliniai asmenys. Matuojamieji parametrai buvo žemės reakcijos jėga (ŽRJ) ir apatinių galūnių momentas. Remiantis momento pasiskirstymu apatinių galūnių sąnariuose, buvo nustatytas tiriamų tipinių ir plokščiapėdžių asmenų atramos momentas.

J. Pauk, J. Griškevičius

GROUND REACTION FORCE AND SUPPORT MOMENT IN TYPICAL AND FLAT-FEET CHILDREN

S u m m a r y

Assessing ground reaction force could provide valuable information in prescribing appropriate footwear to reduce the consequences of flat-foot as well as limiting further complication in flat-feet children. The main goal of this study was to explore the dynamic plantar loading during child walking for. This study examined ground reaction force in 60 flat-foot children and 25 aged-matched control subjects. Measured parameters included ground reaction force (GRF), and the joint moments of the lower limb. The contribution to the support moment from each joint in the lower limb was determined for the control and flat feet groups.

Й. Паук, Ю. Гришкевичюс

СИЛА РЕАКЦИИ И МОМЕНТ ОПОРЫ У ДЕТЕЙ БЕЗ ПЛОСКОСТОПИЯ И ДЕТЕЙ С ПЛОСКОСТОПИЕМ

Р е з ю м е

Оценка силы реакции может дать ценную информацию о выборе соответствующей обуви для детей с плоскостопием с целью уменьшения последствий плоскостопия, тем самым ограничивая дальнейшие осложнения. Основной целью данного исследования является изучение динамической нагрузки стопы детей во время ходьбы. В исследовании участвовали 60 детей с плоскостопием и 25 детей того же возраста из контрольной группы. Измеряемые параметры – сила реакции опоры и момент нижних конечностей. На основании распределения момента в суставах нижних конечностей был установлен момент опоры у исследуемых детей без плоскостопия и детей с плоскостопием.

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