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The Effect of Foot Orthotics on Arch Height: Prediction of Arch Height Correction in Flat-foot Children

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Prognosis of the arch height correction could provide valuable information in prescribing appropriate treatment to reduce the consequences of flat-foot. The goal of this study was twofold. First we explored effect of foot orthotics wedging on the gait pattern of flat-footed children population. Then a simple model to predict arch height correction using six variables was proposed. Measured parameters included the arch height, X-ray measurement, and ground reaction force (GRF). The suggested model allows predicting of the arch height correction. The results show that foot orthotics has small, but a positive impact on the arch height correction.

K e y w o r d s: flat-foot, arch height, X-ray, foot orthotics, regression analysis

1. Introduction

In human foot is a complex system which determines the interaction between the lower limbs and the ground during locomotion. Flat-foot is the most common foot deformity known in children. In fact, 20% of children is flat-footed [1, 2]. Flat-foot is a foot that does not have an arch when standing. In the medical world, flat-feet are associated with the pronated feet. Excessive pronation can lead to unpleasant problems such as: heel, knee, hip, or back pain, bunions, hammertoes, etc. Lack of an appropriate treatment may trigger additional complications including joint deformity, and gait instability [3–5]. The one important characteristics of flat-foot is medial longitudinal arch, which describes the characteristic of body dynamic [6–8]. There are many methods of measuring the medial longitudinal arch [9, 10]. Although most of these methods attempt to quantify the arch, some of them are based on observation. The most important aspect of flat-feet treatment is determining the exact type or

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underlying cause of the flat feet. There are many different treatment options [11, 12]. Children may be treated with some type of support, whether it is molded insoles, special shoes, or braces. Without support holding the foot in the correct position, the bones can develop abnormally, leading to future problems. Foot orthoses are widely prescribed for the treatment of flat-foot, but the biomechanical effect of applied such devices are not fully clear yet.

The main goal of this study was twofold. First we explored effect of foot orthotics on the gait pattern of flat-footed children population. Then we explored whether using a simple model and measuring simple parameters such as age, Cole index, gender, place of living, foot orthotics wedging, and playing sport, correction of the arch height due to flat-foot could be predicted.

2. Materials and Methods

2.1. Subjects

The evaluation was carried out two times (before treatment and two years after applying of the treatment with two types of foot orthotics: for pronation and supination) on 60 flat-footed children (50% of girls) aged between 7–15 years and 70 (40% girls) age-matched control children. Both patients and control subjects were randomly selected from a total population of 1150 primary schoolchildren. The local ethics committee approved the study. All parents received full information about the study before giving signed consent. All subjects were screened with a detailed medical history and were not treated for neither any systemic disease nor flat-feet. Clinical diagnosis of flat-feet was based on observation of ankle dorsiflexion and plantarflexion, rearfoot, midfoot, and forefoot ranges of motion. Inclusion criteria were: age range 7–15, arch height of bilateral feet, knee and hip position, and body symmetry. Exclusion criteria were any other disorders different than flat-feet. Subject's body weight was measured using a scale with resolution of 100 g. The subject's height was measured by stadiometer. The Cole index was used for description the relation between body mass and height [13].

2.2. Measurement Protocol

2.2.1. Measuring Calcaneal Inclination Angle and the Calcaneal-first Metatarsal Angle

Foot parameters were estimated from X-ray measurement taken during fully weight-bearing position at both anterior-posterior and medial-lateral plans. Specifically, the calcaneal inclination angle and the calcaneal-first metatarsal angle were estimated from radiography images to assess foot abnormality [14]. The calcaneal inclination angle was defined as the angle between the tangent to the interferiorsurface of the calcaneus and the platform on which the foot is standing. The calcaneal-first metatarsal angle was defined as the angle subtended by the tangent to the inferior surface of the calcaneus and the first metatarsal [15].

2.2.2. Measuring Arch Height

For measuring of the arch height, the children sat in a chair and placed their feet on level ground. The subjects were tested in random order. The arch height was measured with an optoelectronic system. Three reflective markers were placed on foot while the participants were seated with the subtalar joint in a neutral position. The neutral position of the subtalar joint was defined as the position where talus could be palpated equally on the medial and lateral side of the foot. An experienced physiotherapist placed the markers on the navicular tuberosity, medial aspect of calcaneus, and medial aspect of first metatarsal head. The distance between the floor and the line between the markers on calcaneus and first metatarsal were added afterwards [16].

2.2.3. Measuring of Time of Playing Sport and Foot Orthotics Wedging

Most information about the time spent on playing sport and the time of foot orthotics wedging was obtained from a questionnaire administered by a trained interviewer [17]. The same questionnaire was completed by child and parent separately on the same day. The information gathered was years of playing sport (biking, gymnastics, swimming, playing football, volleyball, basketball, etc.). Children and parents were asked about the children's activity in the last seven years. In the same questionnaire children and parents were asked about the time of foot orhotics wedging (in months) in the last two years.

2.2.4. Measuring Ground Reaction Force (GRF)

The ground reaction force (GRF) for all subjects was measured two times (before the treatment and two years after applying of the treatment) using a force platform. The force data were sampled at a rate of 1000 Hz. Each subject began walking at a sufficient distance from the force plate. For assessing GRF, the subjects were asked to walk barefoot at their habitual speed down the hallway and stop once they reached a predetermined stopping point of 10 meters. Each test was repeated to gather at least five trials, in which the platform correctly measured foot loading. GRF were quantified by three vectors including force vectors in the vertical (Fz), anterior-posterior (Fx) and medial-lateral (Fy) planes. Figure 1 represents a typical pattern of the ground reaction force for flat-footed children.

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 Fz1 (maximum force within first 50% of stance phase), Fz2 (maximum within the second 50% of stance phase) and Fz0 (minimum value between opposite foot off and foot contact). The anterior-posterior ground reaction (Fx) was characterized by Fx1 (maximum posteriorly directed force), Fx0 (minimum posteriorly directed force), and Fx2 (maximum anteriorly directed force). The mediolateral force (Fy) was characterized by Fy1 (maximum lateral force), Fy0 (minimum lateral force), and Fy2 (maximal medial force) – Fig. 1. The forces were normalized to the body mass [N/kg].

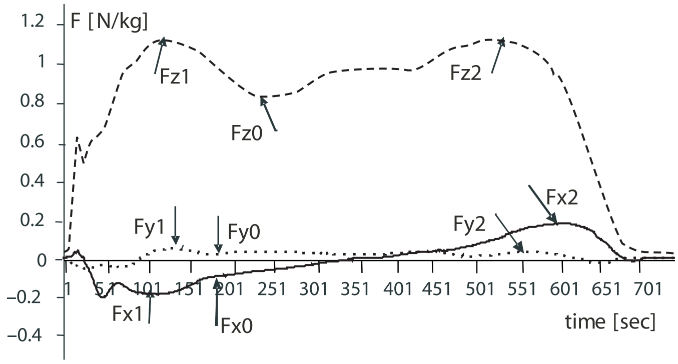

Fig. 1. The typical ground reaction force in flat-footed children normalized to the body mass F[N/kg]

2.2.5. The Model for Estimating of the Arch Height Correction

Considering how difficult it is to determine the effect of foot orthotics on arch height, we explored the feasibility of predicting of the arch height using the regression model (denoted as $\hat{Y}$). A relationship between the dependent and independent variables can be approximately represented within the second degree polynomial [18]:

$$\begin{aligned}\hat{Y} = a_0 + a_1 \cdot X_1 + a_2 \cdot X_2 + a_3 \cdot X_3 + a_4 \cdot X_4 + a_5 \cdot X_5 + a_6 \cdot X_6 + a_{12} \cdot X_1 \cdot X_2 + \\ + a_{13} \cdot X_1 \cdot X_3 + a_{14} \cdot X_1 \cdot X_4 + a_{15} \cdot X_1 \cdot X_5 + a_{16} \cdot X_1 \cdot X_6 + a_{23} \cdot X_2 \cdot X_3 + \\ + a_{24} \cdot X_2 \cdot X_4 + a_{25} \cdot X_2 \cdot X_5 + a_{26} \cdot X_2 \cdot X_6 + a_{34} \cdot X_3 \cdot X_4 + a_{35} \cdot X_3 \cdot X_5 + \\ + a_{36} \cdot X_3 \cdot X_6 + a_{45} \cdot X_4 \cdot X_5 + a_{46} \cdot X_4 \cdot X_6 + a_{56} \cdot X_5 \cdot X_6 + a_{11} \cdot X_1^2 + \\ + a_{22} \cdot X_2^2 + a_{55} \cdot X_5^2 + a_{66} \cdot X_6^2,\end{aligned} \tag{1}$$

where: $\hat{Y}$ is the dependent variable (model output), $X_1 ... X_6$ are the independent variables (model input), $a_1 \ldots a_6$ are model coefficients.

The factors X_3 and X_4 changed into two levels (–1, 1) and it was not possible to analyse their square effects on the arch height (Y). Independent variables in this model were age (denoted as X_1), Cole index (denoted as X_2), gender (denoted as X_3), place of living (denoted as X_4), time of foot orthotics wedging (denoted as X_5), time spent on playing sport (denoted as X_6). To estimate the model coefficients, least square method was used [18, 19]. Gender, and place of living were assigned discrete levels such as: girls (–1), boys (+1); cities (+1), countries (–1).

2.3. Statistical Analysis

To fit the model as well as statistical comparison between the flat-footed and control groups, we examined the agreement between variables' distribution and normal distribution. Outliers were excluded using chi^2 test before the model fitting and statistical analysis. The differences in the ground reaction force was tested with *t-test*. The degree of correlation between the independent variables were examined using the Spearman's rank correlation and presented as follow [18]:

$$r_{x_j x_k} = \frac{\sum_{i=1}^{N}\left(X_{ji}-\overline{X_j}\right)\left(X_{ki}-\overline{X_k}\right)}{\sqrt{\sum_{i=1}^{N}\left(X_{ji}-\overline{X_j}\right)^2\left(X_{ki}-\overline{X_k}\right)^2}}, \tag{2}$$

where: $j, k = 1, 2,...p$, $i = 1, 2,...n$, X_{ji}, $\overline{X_j}$ – the current and mean value of *j*-factor, X_{ki}, $\overline{X_k}$ – the current and mean value of *k*-factor, *p* – sample factors, *N* – sample size.

If $r_{x_j x_k} = \rho_{jk}$ the relationship between factors can be presented as follow:

$$\mathbf{R_x} = \begin{Vmatrix} \rho_{11} & \rho_{12} & \cdots & \rho_{1p} \\ \rho_{21} & \rho_{22} & \cdots & \rho_{2p} \\ \vdots & \vdots & \vdots & \ddots \\ \rho_{p1} & \rho_{p2} & \cdots & \rho_{pp} \end{Vmatrix}, \tag{3}$$

where: $\boldsymbol{R}_{\mathbf{x}}$ – matrix of factor's correlation.

The model coefficient assumed to have no significant impact on the output if the *p*-value was greater than 0.05. The model accuracy was examined using root mean square error (RMSE) scheme between the measured data (*Y*) and the data estimated from the model ($\hat{Y}$). The differences in time of playing sport and foot orthotics wedging declared by children and parents were tested with Landis and Koch categories [20]. Computer software Statistica 8.0 (StatSoft, Tulsa, OK, USA) was used for computations.

3. Results

3.1. Diagnostic of Flat-Foot

The average body mass was 48.2±6.9 kg and 54.7±5.2 kg respectively for flat-footed and control subjects. The flat-footed group demonstrated a significant reduction in the reported pain (37% flat foot children), after applying the treatment with foot orthotics. Figure 2 illustrates a typical X-ray image used for measuring the calcaneal-first metatarsal angle and the calcaneal inclination angle.

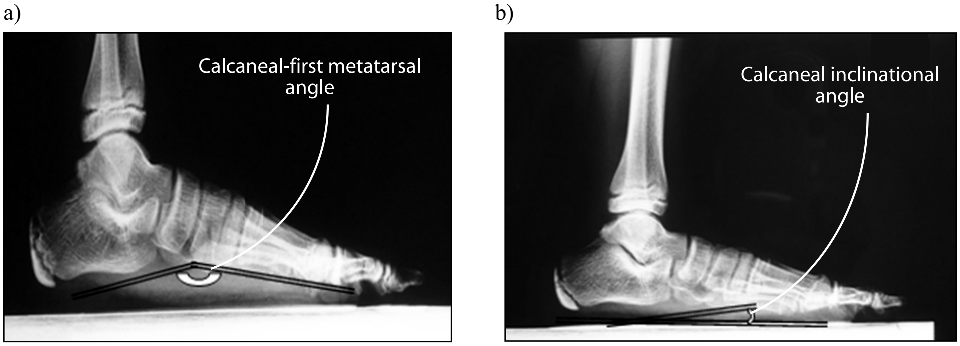

Fig. 2. The typical X-ray image used for measuring the calcaneal-first metatarsal angle and the calcaneal inclination angle

Using radiographic images, the value of the calcaneal first metatarsal angle was ranged between 146°–152° in the control subjects, whereas in the flat-footed patients this angle was significantly higher (155°±9 degrees, $p < 0.05$). However, the value of the calcaneal inclination angle was significantly lower in the flat-footed patients compared to the control subjects ($p<0.05$). Specifically, the calcaneal inclination angle was in range of 21°–26° in the control group vs. 14±5 degrees in the flat-footed children.

3.2. Assessing Ground Reaction Force during Walking with Habitual Speed

The raw ground reaction force data were filtered with a Butterworth filter. Results from the ground reaction force before the treatment suggested that in the flat-footed subjects the maximum of force amplitude in stance phase (Fz1: the first peak – Fig. 1) occurred significantly sooner than in the typical subjects in average by 9% ($p < 0.05$). However, no significant difference was observed for the second peak (Fz2). Force absorption causes an amplitude reduction for the second peak compared to the first one for both flat-footed and control subjects (average reduction values = 0.9%, $p > 0.05$). In anterior-posterior plane, the amplitude of the force in the posterior direction (Fx1) was significantly lower for the flat-footed group (0.17±0.04N for the flat-footed subjects vs. 0.23±0.04N for the control subjects, $p < 0.05$). However, no significant difference was observed for the amplitude of the force in the anterior direction (Fx2) as well as the medial (Fy2) and lateral (Fy1) direction, $p > 0.05$. However results from the ground reaction force obtained after two year treatment with foot orthotics suggest that in the flat-footed subjects the maximum of force amplitude in stance phase (Fz1) occurs sooner than in the typical subjects in average by 7%. However, the difference was not significant ($p > 0.05$). After the orthotic treatment there was observed to be a 0.5% decrease ($p < 0.05$) in the magnitude of the second peak lateral force and a 0.9% increase

($p < 0.05$) in the magnitude of the average medial-lateral force over the stance phase to a less negative value.

3.3. Assessing the Time Spent of Playing Sport and the Time of Foot Orthotics Wedging

The most popular forms of playing sport were bicycle riding (100%), swimming (40%), and playing football (40%). The least popular forms were gymnastic, volleyball, basketball, and dancing. The differences between the child and parent reports were not statistically significant. For most of the analyzed categories of playing sport, significant correlation coefficients ($r > 0.80$) were observed, and the agreement between the child and parent agreement was substantial ($\kappa > 0.6$). Additional, differences between the child and parent reports connected to foot orthotics wedging were not statistically significant, especially in time (in hours/month) of foot orthotics wedging (190.5±13.4 hours by children declaration vs. 182.9±11.2 hours by parents declaration, $p > 0.05$).

3.4. Model Fitting Results

As indicated before, we assumed six independent variables for predicting the arch height correction. The independency between all variables was confirmed by analysis of correlation ($|r| < 0.5$, $p > 0.05$). Specifically matrix R_x represents the correlation analysis between age, Cole index, gender, place of living, time of foot orthotics wedging, and time spent on playing sport.

$$R_x = \begin{Vmatrix} 1 & -0.2121 & 0.0736 & -0.1788 & 0.3215 & 0.4481 \\ -0.2121 & 1 & 0.0793 & 0.1240 & -0.1312 & -0.2725 \\ 0.0736 & 0.0793 & 1 & 0.2013 & -0.2471 & -0.2467 \\ -0.1788 & 0.1240 & 0.2013 & 1 & -0.3260 & -0.4531 \\ 0.3215 & -0.1312 & -0.2471 & -0.3260 & 1 & 0.2808 \\ 0.4481 & -0.2725 & -0.2467 & -0.4531 & 0.2808 & 1 \\ 0.1969 & -0.3724 & -0.1765 & -0.3706 & 0.3890 & 0.4086 \end{Vmatrix}.$$

In addition, the correlation between dependent variable (Y = the arch height) and age, Cole index, gender, place of living, time of foot orthotics wedging, and time spent on playing sport $r_{x1,y} = 0.5794$ ($p < 0.05$), $r_{x2,y} = -0.3706$ ($p < 0.05$), $r_{x3,y} = -0.2489$ ($p < 0.05$), $r_{x4,y} = -0.7064$ ($p < 0.05$), $r_{x5,y} = 0.5821$ ($p < 0.05$), $r_{x6,y} = 0.6147$ ($p < 0.05$). Statistical analysis of the model coefficients showed that the model coefficients (a_{15}, a_{24}, a_{34}, a_{45}, a_{56}, a_{55}, a_{66}) are not statistically significant

($p > 0.05$) and therefore was excluded from the model. The final version of regression model is presented below:

$$\hat{Y} = 14.22 + 2.61 \cdot X_1 - 1.50 \cdot X_2 + 0.35 \cdot X_3 - 2.37 \cdot X_4 + 0.60 \cdot X_5 + 0.11 \cdot X_6 - 1.32 X_1 \cdot X_2 - 1.46 \cdot X_1 \cdot X_3 + 0.76 \cdot X_1 \cdot X_4 - 0.97 \cdot X_1 \cdot X_6 + 1.25 \cdot X_2 \cdot X_3 - 1.30 \cdot X_2 \cdot X_5 + 1.19 \cdot X_2 \cdot X_6 + 0.11 \cdot X_3 \cdot X_5 + 1.48 \cdot X_3 \cdot X_6 - 1.16 \cdot X_4 \cdot X_6 - 0.75 \cdot X_1^2 + 1.08 \cdot X_2^2. \quad (4)$$

The root mean square error between the model output ($\hat{Y}$) and the measured value (Y) was 0.05 mm. The results suggest that the model could accurately fit the measured values ($R^2 = 0.9478$, $S^2_r = 1.4423$). They also demonstrate differences in the arch height correction according to age, gender, Cole index, place of living, time of foot orthotics wedging, and time spent on playing sport. The arch height increased by 40% for boys from cities and by 163.2% for girls as age increased from 9 to 17 years (Fig. 3). Additionally, the results suggest 3.7% for boys from cities and 35.3% for girls reduction for the arch height as Cole index increased from 79.95 to 137.52. However in boys from countries the arch height decreased by 4.9% and in girls increased by 54.4% as age increased. The results showed 2.7% for boys from countries and 27.4% for girls reduction for the arch height as Cole index increased.

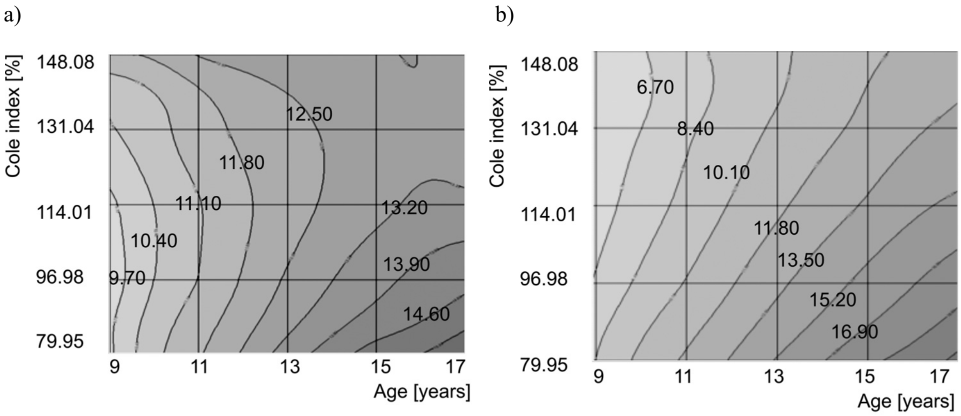

Fig. 3. The impact of age (X_1) and Cole index (X_2) on the arch height correction (Y [mm]) for: a) boys; b) girls, from cities

It was found, that the arch height increased by 12.4% for boys and by 8.9% for girls from cities as the time of foot orthotics wedging increased from 0 to 22 months (Fig. 4).

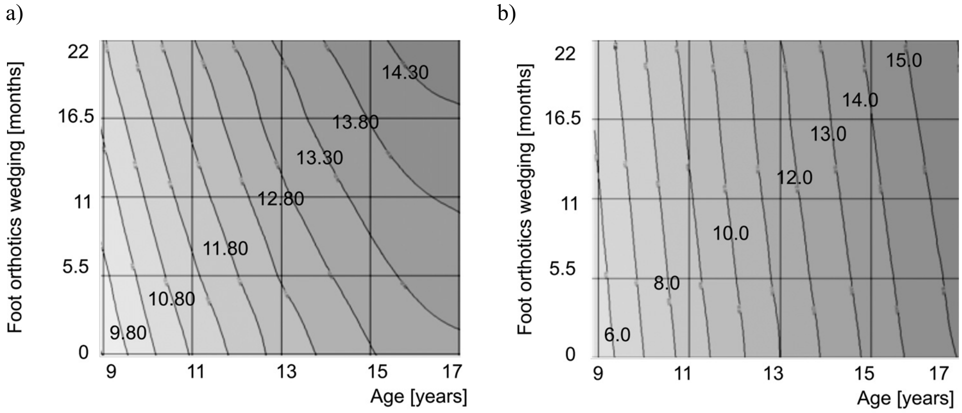

Fig. 4. The impact of age (X_1) and the time of foot orthotics wedging (X_5) on the arch height correction (Y [mm]) for: a) boys; b) girls from cities

The results suggest that the arch increases of 8.7% for boys and 6.2% for girls from countries as the time of foot orthotics wedging increased. Finally, the arch height increased for boys and girls from cities as the time of playing sport increased from 0 to 7 years (7.3% for boys vs. 36.1% for girls). Additional, the arch height increased by 38.8% and decreased by 2.6% respectively in boys' and girls' countries as the time of playing sport increased.

4. Discussion

We explored the feasibility of predicting the arch height correction using simple measurable parameters. Our results demonstrated that using the simple independent variables including age, Cole index, gender, place of living, the time of foot orthotics wedging, and the time spent on playing sport, the arch height correction can accurately be estimated ($r > 0.97$, error < 0.05 mm). The model suggests that the arch height correction as age increased from 9 to 17 years. Staheli [21] found a strong arch height reduction according to age. Other authors admit that major variations on the plantar arch happen until the age of 7 [22, 23]. Some authors, such as Volpon is of the opinion that flatfoot is normal in early childhood and that the condition resolves spontaneously without any treatment. These authors state that the feet of most children who displayed the condition as infants become structurally normal when they are 12 or 13 year old [24]. Our results show, that flat-footed children aged 7–15 years still need a correction.

A significant difference was observed between the city and rural populations. We observed that for girls from cities the arch height (163.2%) was three times higher than for girls from countries (54.4%). On the same note, the arch height for boys from cities 40%) was much higher than for boys from countries (4.9%). Echarri et al. [25] studied the effect of living in the city or countryside as a predictor of flat feet. They demonstrated greater proportion of flat feet in the cities.

Our results show, that the arch height increased for active boys (38.8%) from countries and for active girls (36.1%) from cities. However, in active girls from countries the arch height decreased by 2.6%. This results suggest that in active flat-footed children the arch height correction is higher than in inactive flat-footed children. This finding is consistent with the results reported by Furgal and Adamczyk [26] where they demonstrated intensification of all foot components in physical activity children. In the study they analyzed the difference in the arch height in 100 typical children (50 active children and 50 inactive children) aged from 9 to 10 years.

The model suggests that the arch height correction increased as age and children activity increased. A reduction in body mass produces the higher arch height. It was found the arch height decreasing for boys from cities (3.7%) and from countries (2.7%) as Cole index increased. Additionally the arch height decreased by 35.3% for girls from cities and by 27.4% for girls from countries. These findings are consistent with literatures in which a significant relationship between the arch height and body mass were reported. For example, several studies reported a direct relationship between the arch height and body mass. It has been reported that obese children have a greater tendency for flat foot correction and our results generally agree with those found elsewhere [27]. The relationship between the arch height and body mass has also been reported by Hodžić et al. [28], who determined the impact of body mass on the arch height of 118 children aged between 6 and 9 years.

Our results showed that the effect of foot orthotics on the arch height was not significant. The arch height increased by about 10% for boys and girls as the time of foot orthotics wedging increased from 0 to 22 months. This findings are not consistent with literatures in which a conservative management of patients with flexible flat foot is the form of the treatment recommended by Lovell et al. [29]. However Basmajian and Deluca [30] concluded that muscle activity is not needed to support the arch of the fully loaded foot at rest but only when stress is applied, as at heel off, the aim of exercise is to strengthen the foot muscle only to prevent injuries that may be caused by ligaments laxity. However in the presence of heelcord contracture, stretching exercises are preferred and orthoses are rarely indicated. In contrast, Penneau et al., [31] and Wenger et al. [2] suggested that the use of orthoses could not make permanent changes to the flexible flat-foot. However none of the above reported on the functional outcome of the orthotic treatment.

Finally, in this study, we explored the difference in GRF between flat-footed children before and after the treatment. The results showed that selected variables of the vertical force components were not influenced by foot orthotic use. For example, several studies reported, that one of the functions of the pronation of the subtalar joint is to reduce the vertical impact force during the shock absorption phase which lasts from heel strike to foot flat [33]. The results from ground reaction force obtained after two year treatment with foot orthotics suggest that in flat feet subjects the maximum of force amplitude in stance phase is occurred sooner than in typical subjects in average by 7%.

5. Conclusion

This study suggests a simple model to estimate the arch height correction in flat-foooted children without using any sophisticated technology. Our model suggests that the arch height correction is increased by age and place of living, and decreases as body mass increases. This may suggest a causal link between higher body mass and increased flattening of the arch of the foot during walking. This information is of key importance in reducing the consequences of flat-feet complication via controlling body-weight, physical activity, and the time of foot orthotics wedging.

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