Abnormal biomechanical conditions of the foot in child with Down syndrome during standing: a finite element study

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Abstract

Background: Down syndrome children have a high incidence of pes planus. Pain follows and does harm to their daily life. To well manage their foot pain, it’s necessary to know the mechanism of the pain from the aspect of biomechanics. The purpose of this study was to characterize the abnormal biomechanical conditions of foot in Down syndrome children during standing, comparing to the normal control children by finite element method.

Methods: Two participants aged 5 were recruited in this study that are a Down syndrome child with pes planus and a normal control child. Two three-dimension finite element foot models were constructed from CT of the two participants, each of which include bones, ligaments, plantar fascia, cartilages, epiphyseal plates and an encapsulated soft tissue. The plantar pressure during standing and anthropometric data were collected from the same participants for model validation and simulation.

Results: The abnormal alignment of the transverse tarsal joint showed in Down syndrome child. The contact pressure in Down syndrome child was higher in tibiotalar joint, compared with the normal control child. The tensile force of spring, plantar calcaneocuboid ligaments in Down syndrome child was approximately 9 folds and 58 folds greater than normal control child, respectively. In Down syndrome child contact
force of the talonavicular joint was 0.05 times the body weight and calcaneocuboid joint was near zero, whereas the value in normal control child was 0.11 and 0.01 respectively.

**Conclusion:** The Down syndrome child showed abnormal biomechanical conditions in foot in terms of joints contact pressure, tensile force of ligament around transverse tarsal joint and contact force transmission through transverse tarsal joint. These abnormal biomechanical conditions resulted from pes planus are the potential factors that may cause their foot pain. Conservative interventions should be considered at their early age to eliminate negative effect of these potential factors.

**Keywords:** biomechanics, Down syndrome, finite element analysis, standing, transverse tarsal joint
**Introduction**

Down syndrome (DS) is a genetic disorder with wide spectrum of physical and intellectual disabilities. Musculoskeletal disease represents a serious issue among individuals with DS, and foot deformity is present in almost 60% of all reported orthopaedic issues [1]. It has been reported that pes planus (60-91%) is most universal foot deformity in DS children and inflammatory arthritis (7%) occurred frequently after that and pain follows [2]. The DS children with foot deformity and pain have barriers in walking, balance controlling and participation in physical activities, which induces poor quality of life and imposes heavy burden to the family and society [3, 4].

The radiographic studies about the foot structure in DS children with pes planus showed large talo first-metatarsal angle, low navicular height and calcaneal inclination angle in their feet revealing abnormal alignment of the talonavicular and calcaneocuboid joint [5, 6].

Some studies pointed out that the ligament laxity and hypotonia caused by genetic issue are the main reasons for DS children’s pes planus which induce abnormal alignment of foot [1, 7, 8]. However, some literatures pointed out that the abnormal alignment of talonavicular joint is associated with oblique talus which is congenital and genetic [9]. It’s clear that we can’t prevent the occurrence of the pes planus by the technology of modern medicine, but pain should be well managed at its early stage to develop their gross motor, prevent foot deformity and meet their daily activity demand.
Pain resulted from musculoskeletal disease is strongly associated with abnormal mechanical loading [10]. Though there are many literatures explored the kinematic and kinetic alterations in DS children during walking and standing [11-13], the mechanics of the pain in DS children’s foot is still unclear. Abnormal mechanical loading secondary to adult acquired flatfoot has been fully explored. A finite element (FE) analysis [14] illustrated that posterior tibial tendinopathy, a common reason of adult acquired flatfoot, weakened the load transmission of the joints at the proximal medial column and over-stretched midfoot plantar ligaments, which jeopardize the foot arch and make the foot unstable during gait. However, Christian and his fellows [15] identified the tibialis posterior tendon as a secondary actor in the arch maintenance, compared with the plantar facia and the spring ligament by FE method. Some cadaveric researches found the alterations of mechanical loading such as joint reactive force [16], joints contact pressure [17] to show the implication of foot ligaments by ligament resection. Wong and his fellows [18] found that ligament laxity can result in forefoot abduction and inferred that it may be potentially coupled with pronation and arch collapse. Therefore, fully understanding of the abnormal loading conditions in the foot of the DS children during standing is necessary. Biomechanical research on DS children’s standing may shed new light on the underlying mechanism of foot pain and deformity of them, and will eventually enhance the scientific basis of therapeutic footwear design and testing.
Therefore, this study was aimed to explore the potential source of the pain in DS children from the aspect of biomechanics. Biomechanical conditions of the foot in DS children will be explored by patient-specific FE analysis. The FE analysis, a non-invasive assessment, has been commonly used to investigate the biomechanics of foot and ankle, including pathomechanism, trauma and intervention outcomes [19-21].

**Materials and methods**

**Ethical approval**

All authors declared that all methods in this study were carried out in accordance with relevant guidelines and regulations. The study and protocol were approved by The Human Participants Ethics Committee of the Tongji University (No. 2020tjdxx013). All participants’ parents agreed to participate in the experiments and were fully acknowledged with the purpose and procedures. Since the participants were children (aged 5), written informed consents were obtained from their parents.

**Participants**

One DS and one control children aged 5 were enrolled in this study. The DS child was diagnosed with pes planus. He can stand and walk independently with moderate communicating ability and comprehension. The control child was at the early childhood development stage, and did not present any musculoskeletal pathology. The
anthropometric data including age, height, body weight, foot length, and body mass index were collected (Table 1).

Table 1. Anthropometric information of the participants.

| parameters          | Down syndrome | Control |
|---------------------|---------------|---------|
| Age (years)         | 5.1           | 5.2     |
| Height (cm)         | 99.0          | 106.5   |
| Weight (kg)         | 15.3          | 19.2    |
| BMI (kg/m²)         | 15.6          | 16.9    |
| Foot length (cm)    | 13.9          | 16.2    |
| CIA (°)             | 10.2          | 25.1    |
| TAMBA (°)           | 20.3          | 9.0     |
| Type of foot        | Pes planus    | Normal  |

BMI: Body mass index; CIA: Calcaneal inclination angle; TAMBA: Talus axis-first metatarsal base angle.

**Physical assessment**

The calcaneus inclination angle (CIA) and talar axis-first metatarsal base angle (TAMBA) were measured to identify the foot types of both children (Figure 1). The CIA is an angle between calcaneal inclination axis and the supporting horizontal surface reflecting the
height of the foot whose normal range is 17.0 - 32.0° [22]. TAMBA is an objective criterion to describe the obliquity of the talus as well as the severity of the dislocation of the talonavicular joint, the normal value of which is -3.1 - 9.7° [23].

Figure 1. Schematic diagram of the calcaneal inclination angle ($\alpha$) and talus axis-first metatarsal base angle ($\beta$).

**Finite element modelling**

To construct the two FE models, the Computed Tomographic (CT) images of the right foot was obtained by a 64-layer screwing CT machine (Somatom Sensation Cardiac 64, Siemens Corp., Germany) and two epiphyseal plates were seen at the tibia and fibular in both children from the CT images because of the immature of the bone. The CT images were segmented and processed using commercially available software of Mimics 10.1 (Materialise Inc., Leuven, Belgium) and Geomagic Studio 11 (Geomagic Inc., Research
Figure 2. A flow diagram illustrating the process from CT image, geometrical model and finite element model of the foot. (A): finite element model of Down syndrome child; (B): finite element model of control child.

Twenty-eight bones, 2 epiphyseal plates, 33 cartilages, and an encapsulated bulk tissue were modelled as 3D solid parts in each foot model (Figure 2). The epiphyseal plates were constructed in Hypermesh 11.0 (Altair Engineering Inc., Executive Park, CA,
USA) and were tied to both proximal and distal parts of the tibia and fibular bones. The cartilages were constructed in Hypermesh 11.0 with a thickness of 1.0 - 2.0 mm [24, 25]. The ligaments were modelled as trusses with a cross-sectional area of 1.0 mm² [26]. All the components demonstrated above were then imported in the ABAQUS 6.11 (Simulia, Providence, USA) and then the triceps surae were modelled as a one-dimensional connector in the FE models.

The material properties of the bones, cartilages, epiphyseal plates, ligaments, and plantar fascia were cited from the literatures (Table 2) [27-31]. The encapsulated soft tissue was set as hyperelastic material [32]. The contact between the cartilaginous surfaces were assumed frictionless. The coefficient of friction between foot and ground was 0.5 [32]. The characteristics of ligament laxity of the DS foot was resembled by reducing the Young’s module of the normal foot ligaments by 90% [33].

Table 2. Material properties and element types of the finite element model.

| Component            | Materials | Element types          | Young’s modulus (MPa) | Poisson’s ratio |
|----------------------|-----------|------------------------|-----------------------|-----------------|
| Bone                 | Solid     | 4-node linear tetrahedron | 5000                  | 0.3             |
| Cartilage            | Solid     | 4-node linear tetrahedron | 1                     | 0.4             |
| Epiphyseal plate     | Solid     | 4-node linear tetrahedron | 0.65                  | 0.1             |
|                  |                |                      |       |      |
|------------------|----------------|----------------------|-------|------|
| Ligaments        | Tension only   | 2-node linear truss  | 26\(^a\) | 0.4  |
| Plantar fascia   | Tension only   | 2-node linear truss  | 93.8  | 0.4  |
| Ground support   | Solid          | 8-node linear hexahedron | 17000 | 0.3  |

\(^a\) The Young’s modulus of ligaments for the Down syndrome child; \(^b\) The Young’s modulus of ligaments for the control child.

**Model validation**

In this study, the validation was conducted by comparing the plantar pressure in FE analysis with in-vivo plantar pressure measurement from the same participants [34]. The static plantar pressure of the right foot was recorded by a pressure-sensitive plate (Novel Electronics Inc., Saint Paul, Minnesota, USA). The participants were asked to stand barefoot on the instrument as still as possible for 5 seconds. As the same time, the plantar pressure distribution containing foot-ground pressure value was recorded. The frames contained the first and the last seconds were ruled out and the frames left were averaged in Novel (Novel Electronics Inc., Saint Paul, Minnesota, USA). The data was exported for further validation.
**Boundary and loading conditions**

The proximal ends of the tibia and fibula were fixed. To simulate standing, the ground plate was constrained to allow moving vertically only and half of the body weight was applied on the inferior surface as the ground reaction force. The muscle force of the triceps surae was set as a quarter of body weight [35].

**Results**

The basic characteristics of the two children were showed in Table 1. Based on the normal range of CIA (17.0 - 32.0°) [22] and TAMBA (-3.1 - 9.7°) [23], a lower CIA (10.2°) and a higher TAMBA (20.3°) showed in the DS child indicating abnormal alignment in calcaneocuboid and talonavicular joints. Both CIA (25.1°) and TAMBA (9.0°) of the control child were in the normal range.

**Model validation**

As shown in Figure 3, the peaks of the measured plantar pressure were 0.09 MPa and 0.11 MPa respectively for the two children. Besides, the peak plantar pressure of the DS child and the control child predicted by the FE method was 0.10 MPa and 0.12 MPa. The deviation between the in-vivo experimental measurement and the FE prediction was less than 5% [34]. The region of the peak plantar pressure was both located in the heel, which were consistent with in-vivo experimental measurement. Based on these results, the two FE models constructed in this study were thought to be validated and reliable.
Figure 3. Comparison of finite element models predicted and experimental results on plantar pressure distribution. (A) and (B) showed the results of plantar pressure distribution of Down syndrome child from finite element analysis (A) and experimental measurement (B), respectively; (C) and (D) showed the results of plantar pressure distribution of control child from finite element analysis (C) and experimental measurement (D), respectively.

The contact pressure of the tibiotalar and transverse tarsal joints

Figure 4 present the contact pressure of the tibiotalar and transverse tarsal joints in DS and control children. Compared with the control child, the DS child showed higher contact pressure at the tibiotalar joint (0.81 vs 0.61 MPa) and lower contact pressure at the talonavicular joint (0.34 vs 0.64 MPa). Additionally, the DS child showed abnormal contact pattern in the calcaneocuboid joint comparing to the control child. In the control child, the contact pressure in the talonavicular joint was close to the pressure of the
tibiotalar joint (0.61 vs 0.64 MPa), yet the contact pressure at the talonavicular joint was only 43.21% of the tibiotalar joint in DS child.

Figure 4. The contact pressure of the tibiotalar, talonavicular, and calcaneocuboid joints in Down syndrome child (A, B, C) and control child (D, E, F). (A), (D): The contact pressure of tibiotalar joint; (B), (E): The contact pressure of talonavicular joint; (C), (F): The contact pressure of the calcaneocuboid joint.

**Tensile force of the ligaments**

Tensile force of spring and plantar calcaneocuboid ligaments of two children were calculated. The spring ligament showed a larger tensile force in DS child that is approximately 9-fold higher than the control child. The tensile force of plantar calcaneocuboid ligament in DS child was 7.01 N, whereas the tensile force in the control child was 0.12 N.
**Force transmission**

Foot transmission (in terms of times of body weight) from the hind foot to forefoot of both children during standing was present in Figure 5. The force transmitted through both medial and lateral columns in DS child was lower than that in control child. The contact force of the talonavicular joint in DS child was 0.05 times of the body weight and calcaneocuboid joint was near zero, whereas the value in control child was 0.11 and 0.01 respectively.

![Figure 5. The direction of the force transmission of the Down syndrome foot (red arrow) and control foot (black arrow) during standing.](image)

Figure 5. The direction of the force transmission of the Down syndrome foot (red arrow) and control foot (black arrow) during standing.
**Discussion**

The purpose of this study was to describe the biomechanical conditions of the foot in DS child during standing, and to identify the differences in joint contact pressure, ligament force and force transmission patterns of the foot between the DS and control children. The results showed a higher contact pressure in the tibiotalar joint, a greater tensile force of the ligaments in the midfoot and a lower force transmitted from hindfoot to forefoot in DS child, comparing to the control child. The result predicted alterations in the contact pressure of the joints, tensile force of the ligaments and force transmission, which may provide insight into the foot orthosis design and early clinical interventions for DS.

In this study, the two FE models were validated through the in-vivo experimental measurement of the same participants. Compared with the in-vivo experimental measurement, the FE prediction results showed similar plantar pressure pattern and peak plantar pressure. Based on the comparison, the two FE models and the subsequent simulation results were thought to be reliable.

Contact pressure at the tibiotalar joint of the DS child is higher than the control child, which may increase the risk of getting osteoarthritis leading to foot pain [36]. Limited researches pointed out that children with DS are at increased risk of getting arthritis [37]. But other researchers found that the arthritis of the foot mostly happened after the onset of the pes planus [2, 13]. Though there is no clear evidence showed that
the arthritis in DS is related with the abnormally high joint contact pressure, we still can consider to prevent pain and deformity of foot in DS children.

Compared with the foot in control child, DS foot showed greater force in spring and calcaneocuboid ligaments. The ligaments around joints could strengthen the structure stability [38](Sammarco 2004), whereas larger tensile force of ligaments showed in DS child indicates the joint instability and might induce potential pain in foot and possible rupture of the plantar and medial structures about the medial and lateral longitudinal arches [39].

In our results, lower contact force at medial and lateral columns was observed in the DS foot showing a low efficiency of force transmission from the hindfoot to the forefoot, comparing to the foot of the control child. Since the compression between the bones could prevent the foot arch from collapse and make a more stable foot [40], it’s obvious that the foot of the DS child may have their medial longitudinal arch collapse and stay in a less stable condition during standing. Collapse of the longitudinal arch may lead to progressive valgus of the heel and compensatory varus of the forefoot [41].

Based on our results, the foot structure is another factor, except the ankle stiffness, that induces an inefficient balance strategy. It may require other compensatory strategy involving the hip adopted, resulting in a greater displacement of the centre of pressure in both anteroposterior and mediolateral direction [42]. The potential cause of this abnormal loading pattern is the poor alignment of the transverse tarsal joint and the ligament laxity
A stable joint is linear so that force could transfer along the joint axis and the compression could distributed evenly to the joint surface [40]. However, the talonavicular and the calcaneocuboid joints were both in an abnormal alignment in DS child, which is a reasonable explanation for foot instability, force transmission inefficiency and energy attenuation during standing [43]. The exact relationship between TAMBA and the biomechanical conditions of the DS children need further exploration.

There are still some limitations in this study. Mainly, this study was limited by the single-patient design, predefined set of loading conditions, which was commonly faced by FE study [21]. Given that differences existed in structure between the pathological and normal models, we reconstructed patient-specific DS foot model, which was different from our previous study that constructed the pathological model based on the normal one [33]. Two totally different FE models made the comparison difficult. To minimize this influence, we normalized the contact force by the body weight [34]. Besides, because the weight, height and foot length of DS child was a little lower than the control child, the result of relatively high value in the ligaments and contact pressure in DS child could be thought abnormal.

Additionally, the force of the foot intrinsic muscles was neglected in FE models. In children, little body volume of the body part and thick subcutaneous fat make it difficult to detect precise activity of the foot intrinsic muscles by electromyograph [44]. In the other way, the force of the foot intrinsic muscles was commonly calculated by
inverse dynamics method in previous literatures [21]. However, the deficit of the relation that describes the character of hypotonia in DS children between the muscle length and joint angle makes it impossible to calculate the muscle force. Also, the intrinsic muscles have minimal effect on the FE model since they generated negligible force during standing [35, 45]. Therefore, the simplified foot intrinsic muscles could be thought acceptable.

**Conclusions**

This study explored the abnormal biomechanical conditions in DS child’s foot in terms of joints contact pressure, tensile force of ligament around transverse tarsal joint and contact force transmission through transverse tarsal joint by FE method. These abnormal biomechanical conditions resulted from pes planus may be the potential factors that cause their foot pain. Conservative interventions should be considered at their early age to eliminate negative implication of these potential factors. These biomechanical findings would provide insight into the targeted design of foot orthosis, and clinical interventions for DS children. Future work could focus on design and evaluation on the patient-specific foot orthosis that is suitable for DS children.

**List of abbreviations**

DS: Down syndrome

FE: Finite element
Declarations

*Ethics approval and consent to participate*

All authors declared that all methods in this study were carried out in accordance with relevant guidelines and regulations. The study and protocol were approved by The Human Participants Ethics Committee of the Tongji University (No. 2020tjdx013). All participants’ parents agreed to participate in the experiments and were fully acknowledged with the purpose and procedures. Since the participants were children (aged 5), written informed consents were obtained from their parents.

*Consent for publication*

Not applicable.

*Availability of data and materials*

All data generated or analysed during this study are included in this article.

*Competing interests*

The authors declare that they have no competing interests.

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Authors’ contributions

Concept/design: WXN and YQL, Experiments guidance: BHZ, FE analysis conduct: YQL and DWCW, Main manuscript text writing: YQL, Figures preparation: YW, Revising manuscript content: SJH. Approving final version of manuscript: WXN and MZ. The authors read and approved the final manuscript.

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