

Identification of muscles forces during gait of children with foot disabilities

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1. Introduction

Gait analysis and diagnosis still face some problems of application and knowledge of human locomotion is far from being complete. In many clinical settings mathematical modelling have become an integral part of the clinical decision-making process and of the treatment of gait abnormalities. Mathematical modelling of human movement is one of the challenging tasks in biomechanics. It provides an ability to analyze and experiment with little cost and risk. Many researchers have attempted the simulation of gait by limiting their model with constraints. Many of these take an analytical approach to the synthesis of motion, modelling and designing mobile robots using dynamic optimization [1, 2]. The model incorporated the musculoskeletal system in detail, including the nature of neurophysiology, human control, and stability strategies. Two approaches to modelling of the foot floor interface in forward dynamics simulations of locomotion were discussed by Hatze and Venter [3]. Hemami and Stokes presented an overview of the types of control systems that might be used for the simulation of human locomotion [4]. Each system was founded on neurophysiologic principles. Some of these principles were applied to the control of a 9 link model, in which the initiation of gait was considered. Hurmuzlu has worked in the areas of control and nonlinear stability for successive long-term locomotion cycles. The modelling was initiated based on an inverted pendulum and a simple three element rigid body mechanism in 2D and 3D consisting of a head and trunk (HAT) segment and two rigid legs [5]. Meglan presented a global approach to the analysis of human motion [6]. He developed a comprehensive method for the understanding of dynamic coupling effects in human movement. The skeletal model and the origins and insertions were taken from the work of Crownshield [7], while the ligaments were modelled using the results from a later study by Wismans [8]. Models of gait based on a single concentrated mass were presented by Siegler and Seliktar [9]. This work involved the study of stance phase by imposing initial conditions just before stance and letting the model move through stance without any driving forces. Separate formulations of the dynamical equations of motion were used for single and double stance. Yeadon presented an application of dynamic synthesis to the motion of the human body in athletic aerial manoeuvres [10]. A comprehensive methodology was developed for the determination of kinematics, the modelling of a specific subject using body measurements, determination of the angular momentum of the entire body in flight, and the simulation of the motion using dynamic modelling [7].

The goal of this work is to create 3D mathematical model, which makes it possible to determine forces generated by lower limbs muscles and forces acting on joints.

2. Testing procedures

Functional evaluation was carried out on 60 flat feet children aged between 7-15 years. Patients were recruited into random primary school from Podlasie province in Poland. The optoelectronic SMART system was used for the measurements. The subjects were analyzed while walking barefoot along a straight pathway. Quantization of biomechanical variables and spatio-temporal parameters of walking was performed by means of computerized systems for automatic acquisition of kinematics. The resultant accuracy was assessed by measuring the movement of a special stick with three retro reflective markers placed on it. In these conditions, the only errors that can appreciably affect the kinematic measurements are skin motion artefacts and deformation of the anatomical structure. Pre-processing of raw data involved a tracking procedure, three-dimensional reconstruction of the marker's coordinates, correction for optoelectronic distortion, and filtering. The frequency of acquisition was set at 60 Hz.

2.1. The spatial model of the lower limbs motion

There were taken into account 31 muscles in the muscle system model such as: 1) Gracilis; 2) Adductor longus; 3) Adductor Magnus (extensor part); 4) Adductor Magnus (adductor part); 5) Adductor brevis; 6) Semitendinosus; 7) Semimembranosus; 8) Biceps femoris (LH); 9) Rectus femoris; 10) Sartorius; 11) Tensor fasciae late; 12) Gluteus maximus; 13) Iliopsoas; 14) Gluteus medius; 15) Gluteus minimus; 16) Biceps femoris (SH); 17) Vastus medialis; 18) Vastus intermedius; 19) Vastus Lateralis; 20) Gastrocnemius (MH); 21) Gastrocnemius (LH); 22) Soleus; 23) Tibialis anterior; 24) Tibialis posterior; 25) Extensor digitorum longus; 26) Extensor hallucis longus; 27) Flexor digitorum longus; 28) Flexor hallucis longus; 29) Peroneus longus (fibularis longus); 30) Peroneus brevis (fibularis brevis); 31) Peroneus tertius (fibularis tertius) - Fig. 1.

The lower limb was modelled as a system of three rigid bodies corresponding to thigh, lower leg and foot. All joints were modelled as ball-and-socket joints with three degrees of freedom passing over complicated joints anatomy. The general motion in the 3D Cartesian coordinate system was considered and described with 12 general coordinates: position of the hip joint (x_H, y_H, z_H), notation and

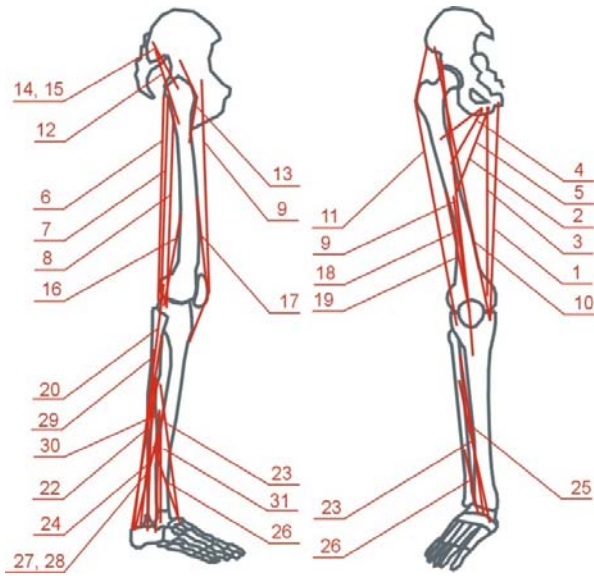


Fig. 1 The muscles taken to the modeling

precession angles as well as longitude of nodal lines of each segment used to model lower limbs.

All coordinates were determined on the basis of experimental investigations carried out with the use of the motion analysis system SMART. During analysis of dynamic equilibrium of all elements gravitational forces, inertial forces, ground reactions, muscle forces and joint reactions were taken into account. Reaction forces as well as the center of pressure, which was used to determine the point of application of reaction forces to foot, were measured during experimental investigations using Kistler dynamometric platform.

It was assumed that the direction of muscle forces, applied to individual segments, corresponds to the line joining current positions of individual muscle origins and insertions. Muscle forces were modelled on the basis of the Hill-like model. Determination of values of muscle forces was carried out with the use of optimization techniques where an effort, put into executing an intended task, was minimized, taking into account muscle characteristics and equilibrium equations.

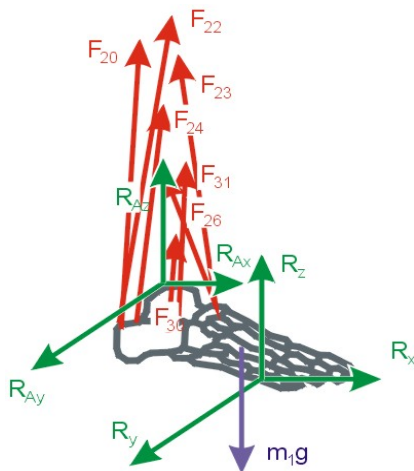


Fig. 2 Force distribution acting on foot

On the basis of force distribution applying on individual elements (Figs. 2, 3), the motion of all segments was described with dynamic equilibrium equations. Then,

using inverse dynamic problem, resultant moments of muscle forces can be determined, which are treated as input quantities in the next stage of calculations where muscle forces are calculated.

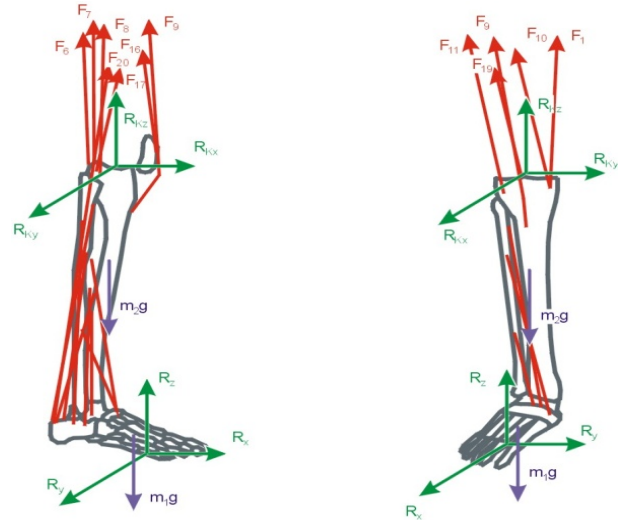


Fig. 3 Force distribution acting on lower limbs

2.2. Identification of muscle forces

One of the most popular methods used to determine muscle forces is static optimization. In the research, presented in this paper, determination of muscle forces was carried out with the use of hypothetical criterion of muscle control where it was assumed that nervous system controls muscles work, trying to minimize loads acting on skeletal system with the objective function of sum of squares of muscle forces

$$J = \min \sum_{i=1}^n (F_{Mi})^2 \quad (1)$$

with the following restrictive condition

$$r_M \times F_M = T \quad (2)$$

$$0 < F_{M,i} < F_{max,i} \quad (3)$$

where n is number of muscle, r_M is a matrix of muscle arms with respect to joints, F_M is matrix of muscle forces, T is matrix of moments with respect to joints derived from external and inertial forces, F_{max} is the maximal force which muscle can generate.

3. Results

In order to carry out identification of muscle forces, the computer program, on the basis of presented mathematical model, was formulated. Conducting analysis of joints reactions, presented in the Figs. 4 - 6, one can notice that the largest values are at the beginning of the stance phase. Probably it can be caused by abnormal feet position – walking on tiptoe. Joint reactions courses for the right and left limb are different, what can show a non-uniform load of both feet. The exemplary results of muscle forces are presented in the Figs. 4 - 6. There are very characteristic differences between the left and right limb, especially for muscles responsible for the foot motion.

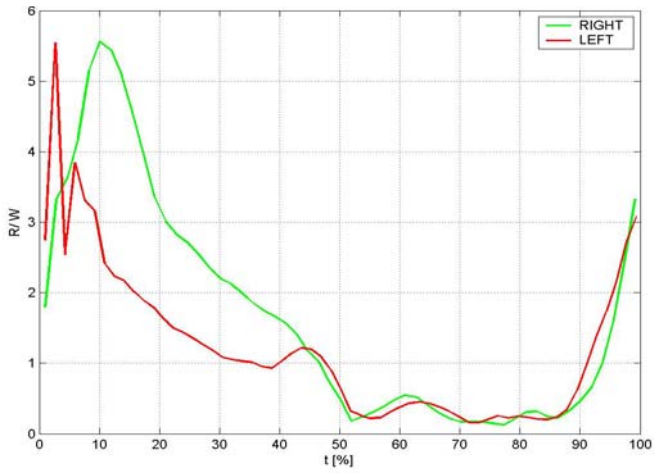


Fig. 4 Resultant reactions in the hip joints during gait for one of the examined child

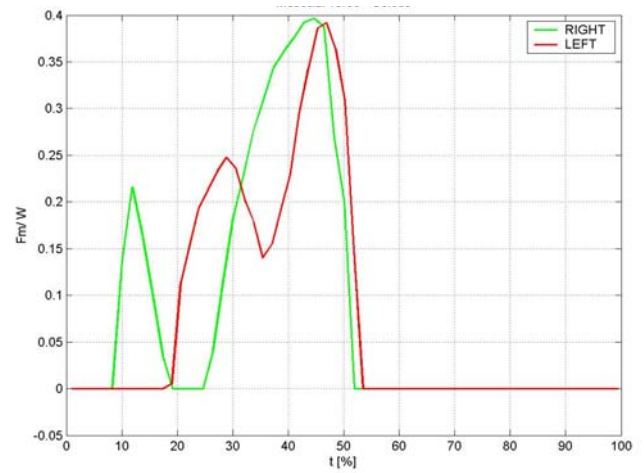


Fig. 7 Muscular forces of Soleus during gait for one of the examined child

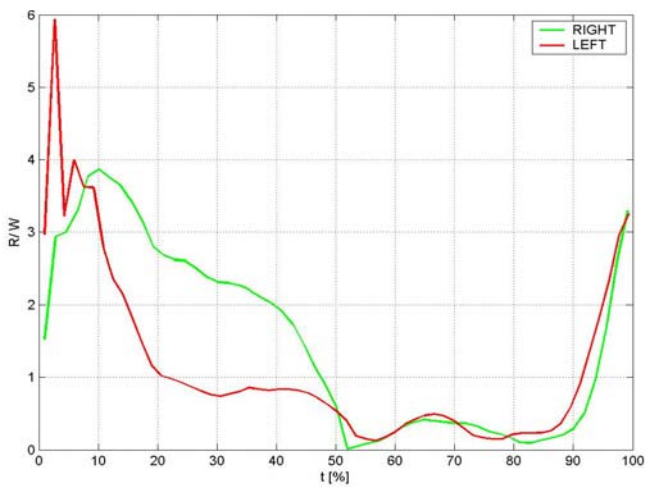


Fig. 5 Resultant reactions in the knee joints during gait for one of the examined child

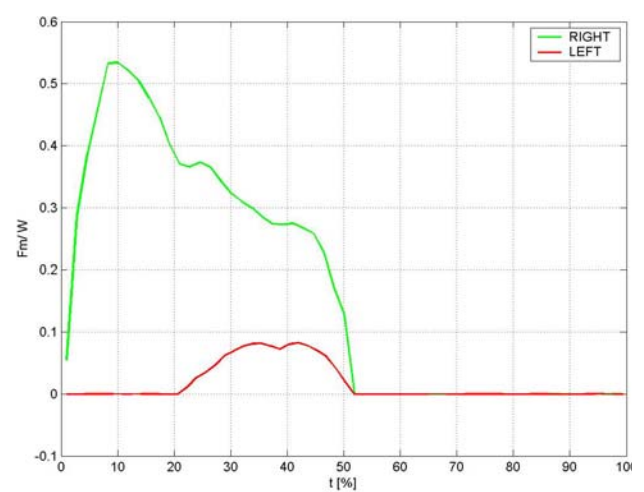


Fig. 8 Muscular forces of Gastrocnemius during gait for one of the examined child

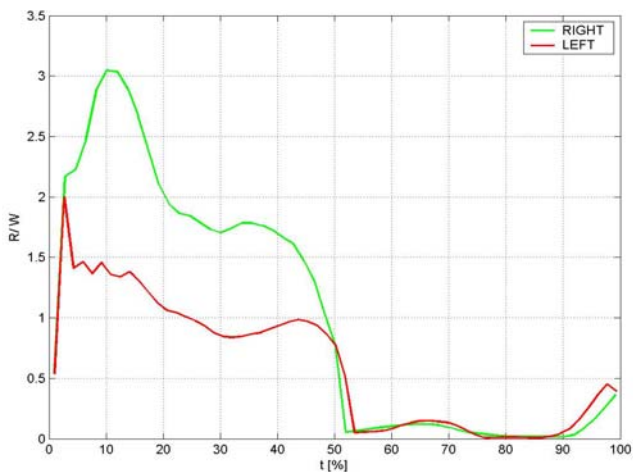


Fig. 6 Resultant reactions in the ankle joints during gait for one of the examined child

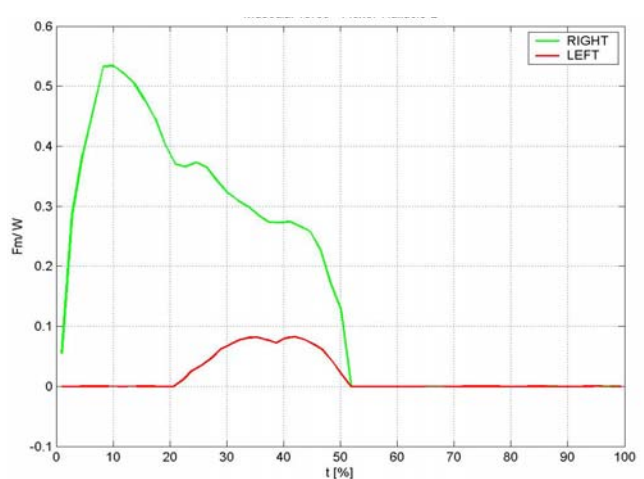


Fig. 9 Muscular forces of Flexor Hallucis during gait for one of the examined child

Forces generated by Gastrocnemius and Flexor Hallucis during the stance phase are relatively small for the left limb. It can show that propulsion in this limb is abnormal. In case of the knee flexors the excessive activity of Biceps Femoris can be noticed both for the left and right lower limb (Figs. 7-10).

The described 3D mathematical model makes it possible to determine forces generated by lower limbs muscles and forces acting on joints. Usage of this model in the computer program makes it possible to determine, in non invasive way, muscle forces and reactions in joints during different forms of motion.

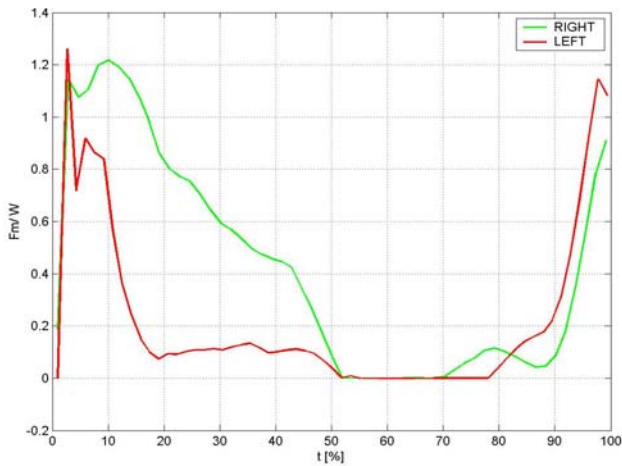


Fig. 10 Muscular forces of Biceps Femoris during gait for one of the examined child

4. Conclusions

The used methodology of experimental and modeling research enables objective qualitative and quantitative evaluation of gait disorders. This methodology integrates measurements of kinematics quantities and ground reactions forces with numerical calculations, where the elaborated mathematical model is the crucial element. The proposed 3D mathematical model makes it possible to determine forces generated by lower limbs muscles and forces acting on joints.

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VAIKŲ, TURINČIŲ PĖDŲ DISFUNKCIJA,
RAUMENŲ JĖGŲ NUSTATYMAS EINANT

R e z i u m ė

Straipsnyje pateiktas eksperimentinis ir modeliavimo tyrimas, leidžiantis analizuoti kojų sąnarių apkrovas. Aprašytas trimatis matematinis modelis leido nustatyti jėgas, sukeltas kojų raumenų, ir jėgas, veikiančias sąnarius.

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IDENTIFICATION OF MUSCLES FORCES DURING
GAIT OF CHILDREN WITH FOOT DISABILITIES

S u m m a r y

The paper presents methodology of experimental and modeling investigation for analysis of loads transmitted by lower limb joints. The 3D mathematical model makes it possible to determine forces generated by lower limbs.

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ОПРЕДЕЛЕНИЕ МУСКУЛЬНОГО УСИЛИЯ,
ВОЗНИКАЮЩЕГО ВО ВРЕМЯ ХОДЬБЫ У ДЕТЕЙ,
ИМЕЮЩИХ ДИСФУНКЦИЮ СТОП

R e z y m e

В статье приведена экспериментальная методика и имитационные исследования, которые включают в себя анализ нагрузки, передаваемой суставом нижней конечности. Описываемая трехмерная математическая модель позволяет определить силу, создаваемую мускулатурой нижних конечностей и силу, действующую на сустав.

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