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CHILD'S MUSCULOSKELETAL MODEL OF THE LOWER EXTREMITIES

Agnieszka Głowacka[1(*)], Robert Michnik[2]

[1]Department of Theoretical and Applied Mechanics, Faculty of Mechanical Engineering, Silesian University of Technology, Gliwice, Poland
[2]Biomechatronics Department Faculty of Biomedical Engineering, Silesian University of Technology, Gliwice, Poland
[(*)]*Email:* Agnieszka.Glowacka@polsl.pl

ABSTRACT

This work contains the spatial model of musculoskeletal system to identify the child's muscle forces and determine joint loads of the lower limbs during gait. The study was conducted in the first place for a healthy child, and then for a child with cerebral palsy.

Keywords: cerebral palsy (CP), gait analysis, mathematical modeling

INTRODUCTION

The management of neurological disorders in children remains a challenge in today's world. Among others, the cerebral palsy affects 2 of 1000 children born worldwide. The early diagnosis and proper treatment reduce disability caused by irreversible damage to nervous system occurring in early stages of development. The treatment strategies consist mainly of physiotherapy, with the adjuvant of surgical procedures. Only in selected medical centers physicians and physiotherapists are supported by engineers, who can aid the treatment planning and monitoring of results by offering objective methods of assessment of the locomotor system. Technological progress enables precise measurement of gait parameters, postural stability and electrical activity of muscles during movement. Digitalization of the gait movements gives possibility to analyze plenty of kinematic variables, yet they do not form the complete picture of movement disturbances. Some values, such muscle forces or load exerted on joints cannot be measured directly but can be estimated using mathematical modelling (Michnik, 2006, 2007, 2009 and 2010). Such engineering methods can divide the complex gait process into motor units which can be described and analysed helping us to understand pathological gait patterns and joint deformities developing in children with lower limbs spasticity.

RESEARCH GROUP

The study involved two children. Healthy child aged 9 years without the musculoskeletal system problems and the child aged 11 with cerebral palsy with left-sided hemiplegia. First experimental tests were performer and involved research of children's gait. Then based on modeling studies identification of muscle forces were carried out and the loads acting on the musculoskeletal system were determined.

THE METHODOLOGY OF EMPIRICAL AND MODEL STUDIES

The numerical computation is carried out on the basis of the inverse dynamics task. Kinematic quantities describing the motion of the limb and the ground reaction forces necessary to perform the calculations are obtained during the experimental measurement using the BTS system (Fig. 1). This system contains:

- six optoelectronic cameras working in the infrared range,
- two dynamometric Kistlers platforms,
- surface electromyography kit BTS Pocket EMG,
- two video cameras,
- computer with software,
- passive markers.

Using this system properly test should be carried out as follows:

- make the subject's anthropometric measurements,
- stick markers at appropriate points on the subject's body (anthropometric points),
- adequately prepare the subject's skin to attach the electrodes.

Anthropometric measurements are needed to calculate because modified Davis's model is implemented in the Smart BTS system software. On the basis of this model the following quantities are determined: the position of the joints center, the kinematic or the dynamic quantities.

Fig.1 Three-dimensional motion analysis BTS Smart system

The mathematical model used in the calculation consists of seven rigid elements (corresponding to the femoral element, the lower leg, foot and pelvis) joint into the kinematic chain, loaded with the forces of gravity, the inertial force and the forces resulting from the contact with the ground and foot (Fig. 2). For such assumptions dynamic equilibrium equations were formulated. These equations are the basis of the mathematical model. Unknown quantities in the equations are resultant joint moments of muscle forces, joint reactions and muscle forces. The inverse dynamics task served to solve the dynamic equations of the motion and calculate resultant joint moments of the muscle forces. The model includes the most important muscle groups responsible for driving and implementing of the movement in all three planes during the gait process (Fig. 3). 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 digitorium longus; 26) Extensor hallucis longus; 27) Flexor digitorium longus; 28) Flexor hallucis longus; 29) Peroneus longus (fibularis longus); 30) Pero-neus brevis (fibularis brevis); 31) Peroneus tertius (fibularis tertius).

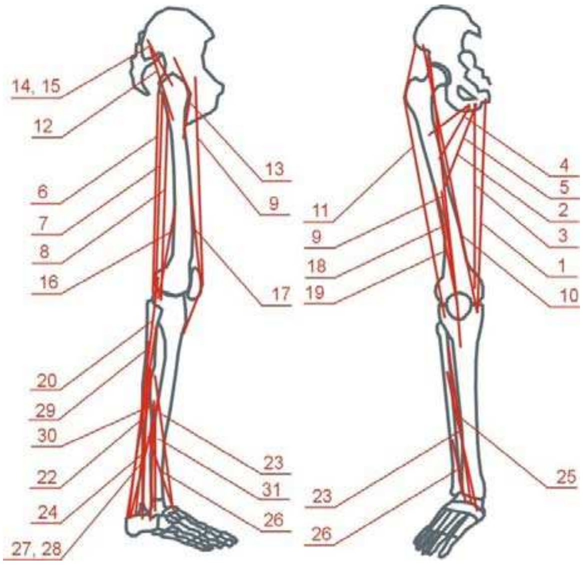

Fig. 2 The muscles taken to the modeling

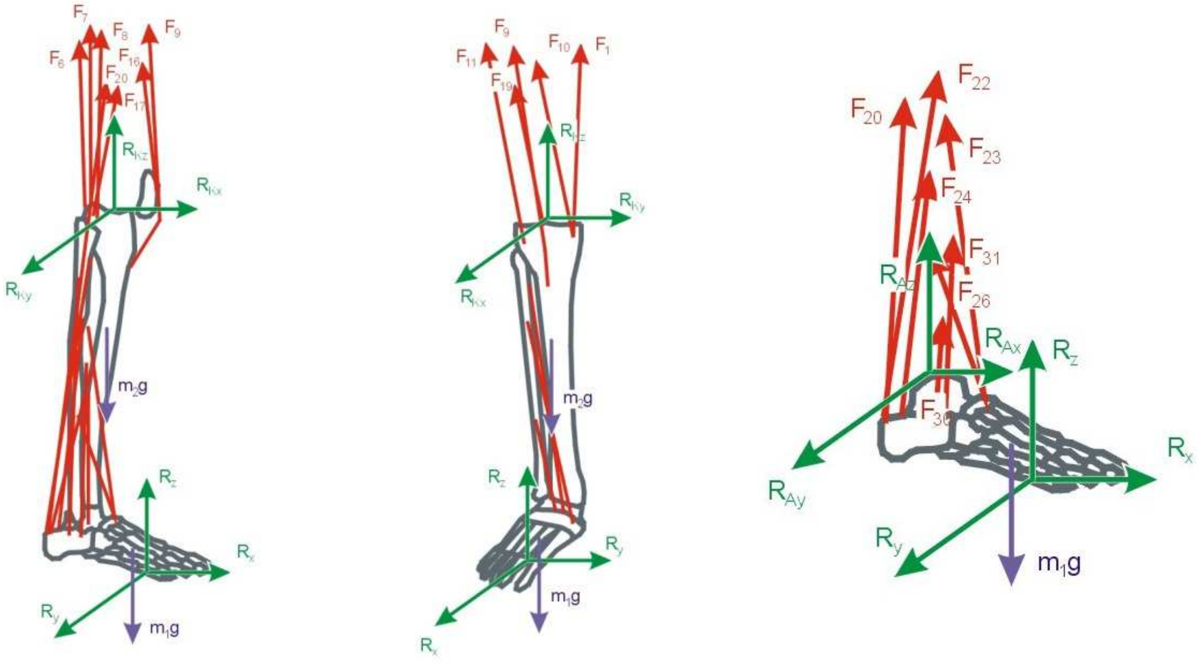

Fig. 3 Force distribution acting on lower limbs

The values of the forces generated by the muscles are determined by the use of optimization methods. The study objective function was as follows – the sum of squares of the muscle forces is minimal (Eq. 1):

$$J = min \sum_{j=1}^{31} (F_m)^2 \tag{1}$$

where F_m is matrix of the muscle forces and restrictive condition resulting from muscle physiology, i.e. the muscle force varies from zero to a maximum value (Eq. 2) and the sum of the moments of the individual muscle forces with respect to joints, which have been designated from the model in the optimization process must be equal moments with respect to joints derived from external and inertial forces (Eq. 3):

$$0 \leq F_{m,j} \leq F_{max,j} \tag{2}$$

$$\boldsymbol{r}_m \boldsymbol{F}_m = \boldsymbol{T} \tag{3}$$

It was assumed that the direction of the muscle forces, applied to individual segments, corresponded to the line joining current positions of individual muscle origins and insertions. The forces generated by the muscles were determined based on the Hill's model.

THE VERIFICATION OF THE MODEL

The verification of the model was based on the measurements of muscle action potentials using the surface electromyography (sEMG) during the children's gait. We examined the following muscle action potentials: Tibialis anterior, Gastrocnemius MH, Gastrocnemius LH, Vastus medialis, Vastus lateralis, Biceps femoris LH. The sEMG research was used for qualitative comparison curves. The numerical analysis allowed to compare the results of the muscle forces obtained from the model with the results of sEMG research of the two selected muscle (Tibialis Anterior, Gastrocnemius LH – Fig. 4) for the healthy child for the right lower extremity. The muscle forces results are shown with respect to the percent of the gait cycle and the body weight, while the muscle action potential courses are shown with respect to the percent gait cycle and the percent of MVC (maximum voluntary isometric contraction). It was found that the muscles are activated normally on the basis of comparison of the muscle forces courses determined by the optimization methods with the measured signal muscle action potentials.

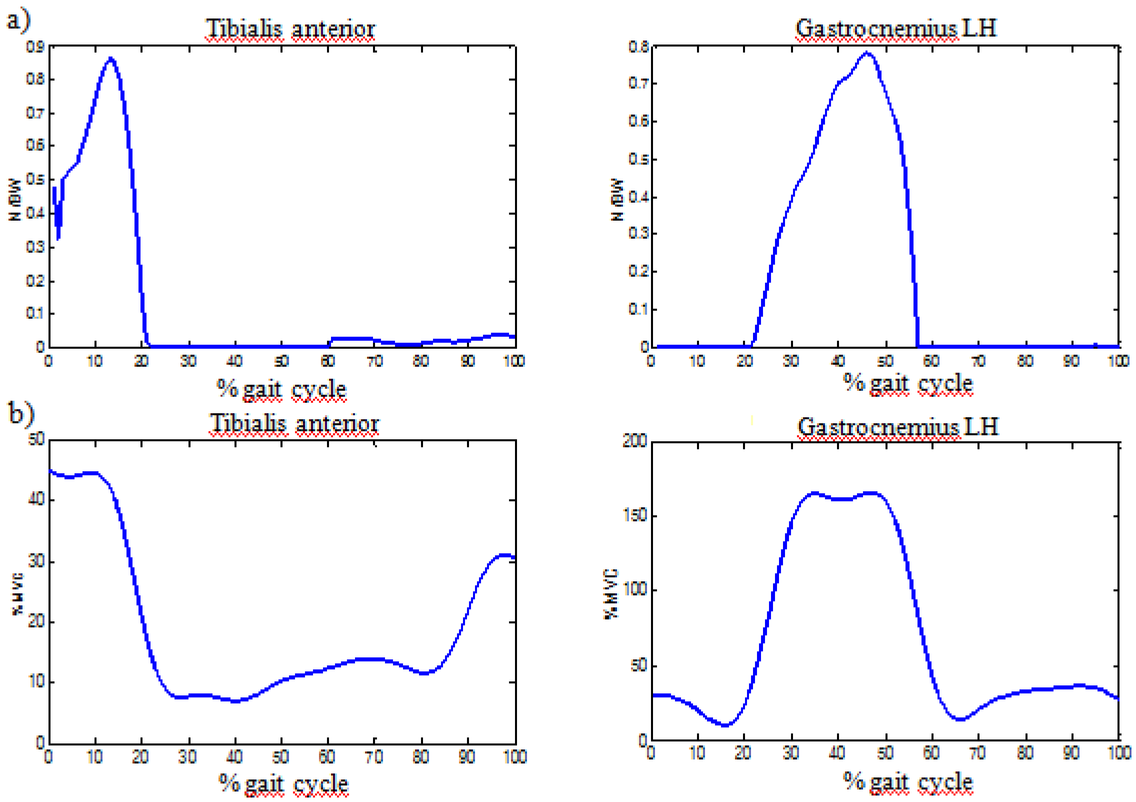

Fig. 4 Courses of a) muscle forces and b) sEMG signals for Tibialis anterior and Gastrocnemius LH

RESULTS OF NUMERICAL COMPUTATION

The gait analysis of children with neurological disorders is very important because it helps in the treatment, diagnosis and rehabilitation of these children. The spatial model of the child's lower limbs motion was used to analyze the muscle forces and joint reactions for the child with cerebral palsy (CP). The muscle forces and joint reactions results are shown with respect to the percent of gait cycle and body weight.

The exemplary results from the numerical computation are shown in Fig. 5-12 (where the green line - a healthy child, blue line – a right limb for a child with CP red line – a left limb of the child with CP).

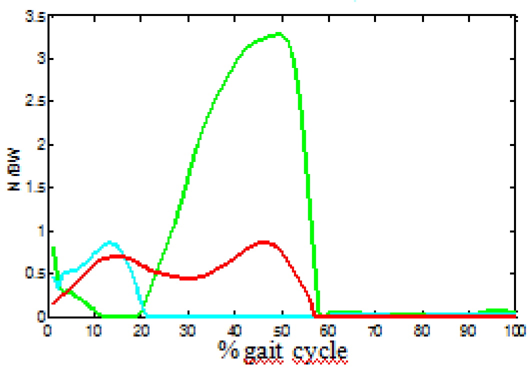

Fig. 5 Muscular forces of Tibialis Anterior

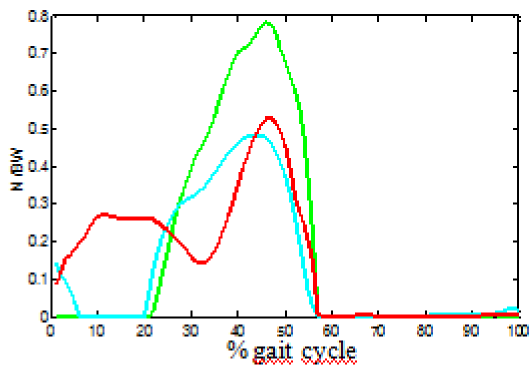

Fig. 6 Muscular forces of Gastrocnemius LH

Tibialis anterior (Fig. 5) has different courses of the muscle forces for both limbs of the child with CP. For the right lower limb this muscle is active between 20% and 60% of the gait cycle (for the healthy child muscle activity is between 0% and 20% of the gait cycle and during the swing phase). The maximum value of the force for that muscle is much greater and it is greater three times than the body weight in the middle of the gait cycle. For the left lower limb this muscle is active throughout the stance phase. Initially, the force value increases, then decreases, and again it increases and the maximum value of the force is about 0.8 of the body weight at approximately 45% of the gait cycle.

For the Gastrocnemius LH (Fig. 6) we can see the differences in the muscle force courses for the child with a left-sided hemiplegia and the healthy child. For the right lower limb this muscle is active between 0% and 5% of the gait cycle and between 20% a 60% of the gait cycle (for the healthy child's muscle activity is only between 20% a 60% of the gait cycle). The maximum value of the muscle force is less as compared to the healthy child and is less than 0.5 of the body weight. For the left lower limb the course of the muscle force of gastrocnemius LH is much different than compared to the normal course. This force increases from the beginning to about 10% of the gait cycle, then decreases to about 35% of the gait cycle, and then increases again to the maximum value, which is more than half of the body weight in the middle of the gait cycle. The muscle forces decreases rapidly between 50% a 60% of the gait cycle and this muscle is inactive the whole swing phase.

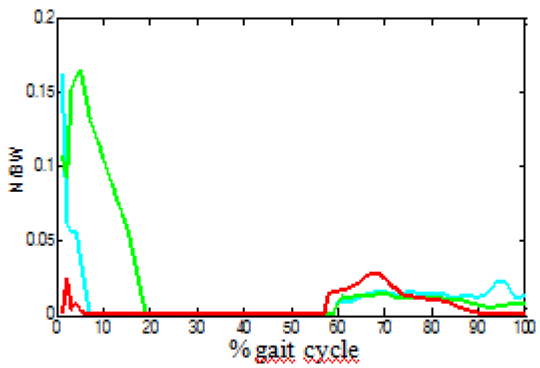

Fig. 7 Muscular forces of Vastus lateralis

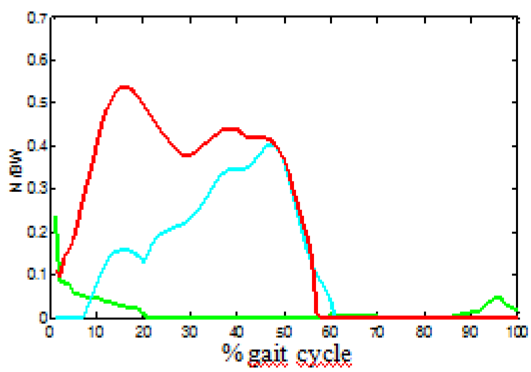

Fig. 8 Muscular forces of Semitendinosus

Vastus lateralis (Fig. 7) has different courses of the muscle forces for both limbs of the child with CP compared with the healthy child. For the right lower limb this muscle is active between 0% and 8% of the gait cycle (for the healthy child muscle activity is between 0% and 20% of the gait cycle) and during the whole swing phase as the healthy child. The maximum value of the force for that muscle is 0.16 of the body weight and occurs at the beginning of the gait cycle. While for the left limb muscle activates incorrectly between 0% and 10% of the gait cycle as compared to the healthy child. The value of the force is small, and in this range has the maximum value and equals about 0.02 of the body weight. During the swing phase, the muscle is active from about 60% to 90% of the gait cycle. Within this range, the value of the force is the greatest and it is equal to about 0.03 of the body weight at 70% of the gait cycle.

The course of the muscle force for semitendinosus (Fig. 8) is much different for the child with CP. For the right lower limb this muscle is active between 5% and 60% of the gait cycle, and the maximum value of the force is about 0.4 body weight in the middle of the gait cycle. For the left lower limb this muscle works in the whole stance chase and the maximum value of the force is more than half of the body weight at approximately 15% of the gait cycle.

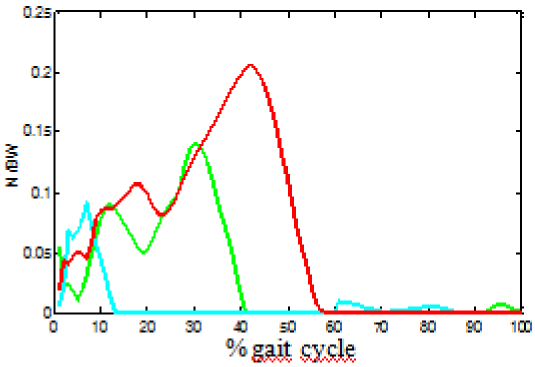

Fig. 9 Muscular forces of Gluteus medius

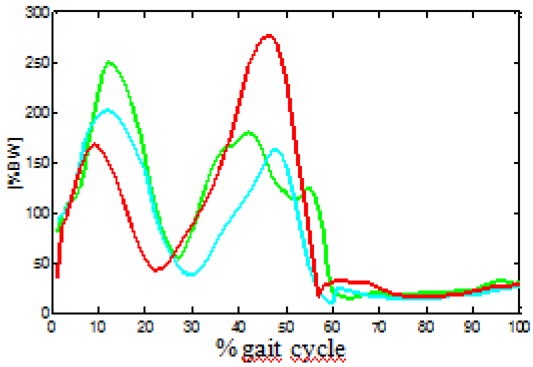

Fig. 10 Resultant reactions in the hip joints

For the child with CP Gluteus medius (Fig. 9) is changed the courses of the muscle forces for both limbs. For the right lower limb the muscle is active shorter in the stance phase (up to about 15% of the gait cycle) compared with the healthy child (up to about 40% of the gait cycle). The maximum value of the force is about 0.09 of the body weight at approximately 5% of the gait cycle. For the left lower limb Gluteus medius works in the whole stance phase. The maximum value of the force is 0.2 of the body weight at approximately 40% of the gait cycle.

The reaction in the hip joint (Fig. 10) is different for both limbs for the child with the left-sided hemiplegia as compared to the healthy child. The differences are also visible in the maximum values of reactions in the hip joint. For the child with CP the maximum value of reactions in the right hip joint is equal double body weight and there is a little above 10% of the gait cycle (for the healthy child is about 2.5 of the body weight). For the left lower limb this value is less than 2.8 of the body weight and is about 45% of the gait cycle.

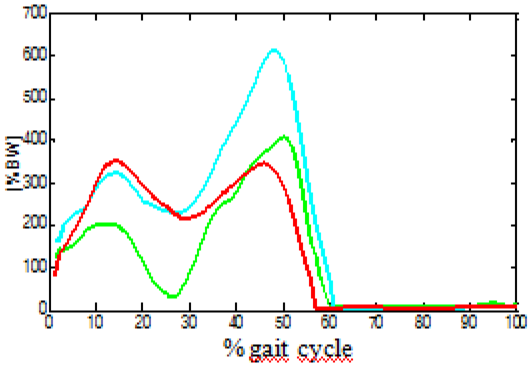

Fig. 11 Resultant reactions in the knee joints

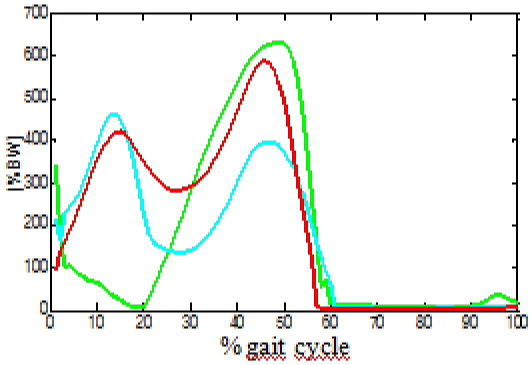

Fig. 12 Resultant reactions in the ankle joints

The next figure 11 shows reaction in the knee joint, where we can see the differences for the healthy child and the child with a left-sided hemiplegia. For the child with CP the maximum value of reactions in the right knee joint is more than six times of the the body weight. For the left lower limb this value is about 3.5 of the body weight and it occurs much earlier about 15% of the gait cycle.

The significant differences can be seen for the course and the reaction in the ankle joint (Fig. 12). For the child with CP the maximum value of reactions in the right ankle joint is between 10% and 15% of the gait cycle and it is more than four times of the body weight. For the left lower limb this value is more than five times of the body weight at approximately 45% of the gait cycle.

CONCLUSION

This study shows that there are differences in the forces generated by the muscles and the joint loads of the lower limb for a child with cerebral palsy. This analysis allows to determine anomalies in the musculoskeletal system. In the future, it will be a useful tool for physicians in making decisions about surgery, pharmacological treatment, rehabilitation, or tracking the progress of treatment and rehabilitation.

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