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Original Research Article

Use of the surface electromyography for a quantitative trend validation of estimated muscle forces

Q1 *Magdalena Żuk* [a,*], *Malgorzata Syczewska* [b], *Celina Pezowicz* [a]

[a] *Wroclaw University of Science and Technology, Faculty of Mechanical Engineering, Wroclaw, Poland*
[b] *Department of Paediatric Rehabilitation, The Children's Memorial Health Institute, Warsaw, Poland*

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ABSTRACT

Surface EMG is a non-invasive measurement of an individual muscle activity and it can be used as the indirect form of a simulated muscle forces validation. The quantitative curves comparison has some potential, which has not been fully exploited yet [13]. The purpose of current study was to quantitatively compare muscle forces predicted using musculoskeletal models to measured surface electromyography signals. A metrics based on correlation and an electromechanical delay correction for a quantitative trend validation has been proposed.

Kinematics of a normal gait was collected for three healthy subjects together with ground reaction forces and EMG signals of eight different muscles of both legs. Dynamic simulations have been performed for two models of differing complexity from OpenSim library (Gait2392 and Gait2354) [2,5,6], static optimization method and *computed muscle control* algorithm [20] have been used. It has been shown, that the level of force-EMG trend compliance, obtained for applied models and simulation techniques, is related rather to the selected muscle than to applied optimization criteria or technique. The contribution of analyzed muscles during gait has been predicted better by complex model than by simplified model. Moreover relationship between the body proportion of subject and the degree of correlation has been observed. Proposed metrics and obtained results can be the basis for further identification of cost functions, which could most closely describe motor control strategy.

1. Introduction

Currently developed, complex multibody models of the human movement apparatus and dynamic simulation techniques allows for a estimation of the joint moments, load in the joints or muscle forces. Generally an inverse dynamic approach is used to estimate muscle forces, where modeling process includes: measurement of joint kinematics using motion capture system [24,25] and ground reaction forces

* *Corresponding author at*: Wroclaw University of Science and Technology, Faculty of Mechanical Engineering, Wroclaw, Poland.
E-mail address: magdalena.zuk@pwr.edu.pl (M. Żuk).

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using force platforms, calculation of muscular joint torques on the basis of multibody system and experimental data, and solution of muscle force sharing problem using optimization techniques [8,17]. Musculoskeletal modeling has great application potential. However, the widespread implementation of these methods in clinical practice, including planning of surgical treatment and rehabilitation process, design of personalized implant or orthopedic and rehabilitation devices, should be preceded by the validation and verification [12]. A comprehensive evaluation presents a huge challenge due to a very limited measurement capabilities, complexity of the human locomotion system and an interindividual variability. Direct validation of estimated muscle forces is possible by measuring of joint load using telemetric prosthesis [11] or in vivo measured tendon forces using force transducers measurement [8], while among noninvasive validation methods are electromyography and sensitivity analysis [26]. So far, the most common form of validation of estimated muscle forces was the electromyography. An extensive summary can be found in the paper of Erdemir et al. [8]. Many authors compared the estimated muscle forces to the timing of onset and offset resulting from EMG signal [4,15,16,22], which stems from the fact, that the presence of myographical signal is the condition for muscle force generation. However, such analysis does not fully exploit an information carried by EMG signal [13]. Only an amplitude of myography signal, dependent on number of involved muscle fibers, is highly correlated with a muscle force. Muscle electrical activity does not give the direct information about the force. However it allows to asses, if muscle is less or high activated, while a muscle force increases with an activity. The qualitative comparisons of estimated muscle forces curves and measured EMG signals have been presented in several papers [2,9,14,19,21]. The quantitative assessment requires development of quantitative validation metrics and some assumptions. So far, there are limited number of such quantitative analysis [10,18]. Prilutsky and Zatsiorski compared muscle forces during cycle of walking calculated for one typical subject to averaged EMG signals obtained for 10 subjects [18]. Muscle forces were estimated using static optimization for simple, two-dimensional model of the human leg controlled by nine muscles. Heintz and Gutierrez-Farewik have performed quantitative comparison of muscle forces from static optimization to normalized EMG signals for one typical subject [10]. According to the authors knowledge, previous quantitative analysis did not include forward assisted data tracking techniques (e.g. CMC *Computed Muscle Control* [20]).

The purpose of current study was to quantitatively compare muscle forces predicted using musculoskeletal models to measured surface electromyography signals. In the study quantitative validation metrics based on correlation and an electromechanical delay correction have been proposed and applied. Indirect validation of musculoskeletal models and simulation techniques using EMG signal for a quantitative trend validation has been discussed. In this study, two, freely available models with different number of muscles and different simulation techniques, including static optimization methods with different criteria and CMC algorithm, were compared. Dynamic simulation was performed for three subjects with varying body structure.

2. Methods

Three able-bodied subjects without walking disability (one male and two females) were analyzed (aged mean 25 years, height mean 171 cm and weight mean 63 kg). Detail subject's data are presented in Table 1. The study was approved by the Local Ethical Committee. All participants provided written informed consent before participation. The subjects walked barefoot at the preferred speed while simultaneously kinematics data, ground reaction forces and EMG signal from selected muscles were captured.

2.1. *Data collection*

Gait kinematics was captured using VICON 460 (Vicon Motion Systems Ltd., Oxford, UK). Motion capture system equipped with six cameras, which recorded markers location sampled at 100 Hz. Modified Plug-in-Gait model was applied with twenty-one reflective markers located on arms, pelvis and lower limbs as shown in Fig. 1. Ground reaction forces (three components) were measured using two Kistler force plates (Kistler Holding AG, Winterthur, Switzerland). EMG system (MotionLab-Systems, Inc. USA Motion Lab Systems, Inc., Baton Rouge, USA) for dynamic surface dynamic electromyography recorded EMG signal with sampling frequency 1000 Hz. Signals were bilaterally collected from gluteus medius muscle, biceps femoris muscle, vastus lateralis muscle, gastrocnemius muscle (medial and lateral heads), tibialis anterior muscle, peroneus longus muscle and soleus muscle. Surface electrodes were placed according to SENIAM recommendations. The kinematics, kinetics and electromyographic systems were synchronized.

2.2. *Musculoskeletal modeling and dynamic simulation*

Dynamic simulations were performed using OpenSim 3.0.1 software [6], together with Gait2392 [1,2,5,23,27], freely available musculoskeletal model included in OpenSim library. 23 degrees of freedom multibody model consists of 12 rigid segments: pelvis, torso, tights, shanks, calcaneus and toes. A model is driven by set of 76 muscles represented by 92 actuators (Fig. 1). Also a simplified Gait2354 model with reduced number of actuators (54 actuators, which represent 49 muscles) was used. Detailed comparison of both models can found in OpenSim documentation [27]. General models were scaled to subjects anatomy using basic OpenSim scaling tool on the basis of measured marker locations and body mass. Manual adjustment of virtual markers placement was done during scaling process in order to accurate anatomical calibration of computer model. Then, for each subject following dynamic simulations of muscle forces were performed using scaled Gait2392 model: static optimization with three different criterions (minimization of sum of a, a^2 and a^3, where a is an activation level) and forward assisted data tracking method called CMC (*Computed Muscle Control*) [20]. For scaled reduced models Gait2354 static optimization with default criterion (minimization of sum of a^2) and CMC simulations were performed.

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