Abstract

Gait is the main form of human locomotion, and its study is the primary tool for assessing the condition of the musculoskeletal system. Standard clinical reports do not take into account the forces generated by individual muscles due to the invasiveness of their direct measurement. To estimate them, modelling methods are used, among which the most common are static optimization using various criteria and objective functions.

The purpose of the study was to develop a method for applying a mathematically advanced minimum fatigue criterion to models composed of multiple muscles and to create a procedure to determine a criterion consistent with that selected by the human central nervous system in solving the muscle force-sharing problem during gait. The application goal of the research was to create the possibility of extending gait analysis protocols with additional information about the contributions of individual muscles to the execution of a movement and to demonstrate that this can prove important in making diagnostic decisions.

To achieve these goals, a complex model of the lower limb with 45 muscles was developed to provide the data needed to formulate constraints in static optimization. Then, a procedure was prepared to allow to solve the problem of muscle force sharing for such a complex model for the criterion of minimum fatigue by the method of feasible sets. This criterion has not been effectively used for such complex models before due to the difficulty of solving the optimization task with a non-linear objective function. The problem of muscle force sharing was solved for the physiological gait and two cases of pathological gait, for each limb separately. In addition to the minimum fatigue criterion, calculations were made for polynomial criteria with the second and third power and for the soft saturation criterion. In polynomial criteria, shift parameters with different values were used. Then, a procedure was developed to select the best criterion using the similarity index, which allows the comparison of muscle activation obtained by the optimization method with the recorded EMG signals for selected muscles.

The best similarity results with EMG signals were obtained for the minimum fatigue criterion or the polynomial criteria with a shift parameter. Statistically significant differences in the similarity index values obtained for these criteria in comparison with the commonly used quadratic criterion were found. Based on the optimization data on the involvement of individual muscles in the performed movement, detailed biomechanical analyzes were prepared for cases of physiological and pathological gait. These analyses demonstrated the usefulness of supplementing standard gait reports with this information, which are usually limited to the

resultant moments of forces and resultant powers. In particular, the study obtained results confirmed how important it is for pathological gait to use a criterion that can provide information about the involvement of antagonistic muscles in joint stabilization. It has been shown that limiting the analysis to information about the resultant moment only may lead to incomplete conclusions. It was also shown how the knowledge of the involvement of individual muscles makes it possible to conclude that their action differs from the activity in the physiological form.

The results obtained in the study lead to conclusions that may be of significant importance in practice, as they justify the validity of using the minimum fatigue criterion and criteria with the shift parameter in solving the problem of muscle force sharing for pathological gait, which is noteworthy because these criteria have been neglected in such applications.

Keywords: gait analysis, pathological gait, muscle force sharing, static optimization, musculoskeletal model, polynomial criteria, soft saturation criterion, minimum fatigue criterion, criteria with shift parameter