Experience in the Development of Rehabilitation Exoskeletons

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Questions of the software and technical production of exoskeletons supporting stable gait for patients are discussed, along with the recording and analysis of electrophysiological data allowing changes in the status of the body during rehabilitation to be determined.

Introduction

One effective means of rehabilitation of patients with lesions to the musculoskeletal apparatus consists of using exoskeletons providing support for complex types of movement in patients: verticalization, sitting down, walking, etc.

The first stage of studies in this area at the South-West State University, in which the authors have directed and taken active part, consisted of developing an exoskeleton providing verticalization of patients. The structure of this type of exoskeleton and the principles of its stable control have been described in considerable detail in [1, 2]. With the aim of minimizing the risks for weak patients, the control system of Exoskeleton includes devices monitoring electrophysiological parameters (electrocardiogram and arterial blood pressure).

The results obtained by processing the electrophysiological data recorded are transmitted to the physician for subsequent analysis and decision-taking, and are also used for controlling the servo motors in the lifting mechanisms using biotechnological feedback circuits. Where necessary, this allows verticalization to be stopped or its speed to be altered.

The second stage addressed the challenge of developing an exoskeleton with stable gait and improved control of the functional status and patients’ state of health with the aim of increasing the effectiveness of the rehabilitation process.

Analysis of existing solutions showed that the most widely used devices in world practice are those produced using combined schemes organizing movements when crutches are used in the exoskeleton to maintain the patient’s balance. These devices include exoskeletons such as the Ekso Bionics, ExoAtlet, and others, made in various countries [1, 3].

However, this means of movement requires serious physical preparation of the patient with development of the arms, and restricts movement convenience. Movement of the patient in an exoskeleton with maintenance of the stability of the vertical position without crutches or any other means of support is currently achieved by only one exoskeleton, made by Rex Bionics. The Rex Bionics device allows patients to verticalize, walk straight ahead and behind, turn, and get up from bed.

The aim of studies conducted at the South-West State University was to create a Russian exoskeleton with a stable gait without using any accessory devices and with extended functional capacity in the rehabilitation process [4-6].

Control System for Stable Exoskeleton Gait

In developing an exoskeleton control system supporting vertical gait, we investigated three main solutions:

1) control in slow movements in which inertial forces induced by acceleration of parts of the exoskeleton are small compared with weight forces;

2) movement of the exoskeleton with acceleration on smooth surfaces, where not only normal reactions but also friction forces have to be considered;

3) movement of the exoskeleton on uneven surfaces, when not all sensors used for assessing normal reactions are in contact with the support surface.
The challenge of stable control of the exoskeleton was addressed using the zero moment point (ZMP) method as defined by Vukobratović [7].

The center of gravity of the exoskeleton (CGe) and the ZMP are virtual points whose positions in space can be determined only by computational methods based on kinematic analysis for CGe and dynamic analysis for ZMP. The positions of these points within the support surface allow the stability reserve (SR) of the exoskeleton to be evaluated. Positioning of the CGe or ZMP at the center of the support surface maximizes SR. The closer the CGe or ZMP to the boundary of the support surface, the greater the possibility of loss of exoskeleton stability and, thus, the smaller the stability reserve.

During these studies, we obtained analytical expressions for determining the stability reserve allowing for normal reactions and friction forces; we proposed a scheme for positioning pressure sensors on the foot to determine normal reactions $N$, which are used in computations of the stable state of the exoskeleton on even surfaces (Fig. 1a).

Stability on walking on uneven surfaces requires the use of a special construction for the suspension of the flexible or deformable foot (Fig. 1b). A “floating” foot, adapting to the road surface profile (see Fig. 1c), could be used. This version of a “flexible foot” includes a multilayer composite structure for the sole, allowing foot muscles to operate and making gait more natural.

Apart from sensors for normal reactions and friction forces, a stable gait requires the exoskeleton to be fitted with local navigation systems allowing accurate determination of the distance from the foot to the support surface in both the vertical and horizontal planes (Fig. 2, a and b).

A general control scheme for a stable exoskeleton gait is shown in Fig. 3.

Solution of the stable control challenge involves a measurement subsystem (Fig. 3) containing video camera 1; sensors for the rotation angle 2; pressure sensors 3; inertial navigation system running in an IMU module 4; rangefinders 5.

The control system for stable exoskeleton gait has a data processing system with measuring devices and a smart decision-taking system. Servo motors are controlled by signals delivered via power amplifiers (PA). Use of this data processing system provides the exoskeleton, with or without the patient’s involvement, with the abili-