THE ARCHIVES OF TRANSPORT

VOL. XXVII-XXVIII NO 3-4 2013

Effect of user's individual features on energy consumption of the orthotic robot

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Received September 2013

Abstract

While working on a system for verticalization and aiding the motion of the disabled, the problem emerged related to evaluation of the effect of individual traits of the users of the system on the obtained characteristics of the actuators. Studies that have been carried out so far, were limited strictly to a case of an ordinary male. The traits of the user will significantly influence operation of the robot, therefore it was decided to carry out studies within a wide range of variability of the basic anthropometric traits. The paper presents a way of determining parameters, which were being changed during the studies, as well as a general structure of the simulation model. Then, a method of computing the energy consumed by the actuators is described, and results of the realized simulation experiments are presented.

1. Introduction

Orthotic robot is a device, whose task is to restore lost or weakened functions of the limbs of the handicapped person. It belongs to a group of devices called 'wearable robots' [8], i.e. being some kind of clothing for the user. At present, similar projects are run in a few centres in the world; their common task is an innovative approach to the issue of how the disabled can move around [2, 3, 4, 7]. It relies on employing technical devices in such a way as to not only provide the disabled with a possibility of moving, but also so that they can move in the manner of a healthy individuals. The system for verticalization and

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aiding motion of the disabled, that has been designed within the ECO-Mobility project, is aimed to make it possible for individuals suffering prom paralysis of the lower limbs, who have used wheelchairs so far, to move in a vertical attitude. Mechanical structure of such robot is fastened to the lower limbs of the user, and by means of electric motors it forces the movements of limbs of the disabled person, thus making a gait possible, with a vertical attitude kept at the same time. Ultimately, the system is to be designed for a widest possible group of users. Each of the future users will have individual anthropometric parameters, which are the main source of the loads transmitted by the actuators of the device. Therefore, it is necessary to evaluate the influence of the individual traits of the users on the operation of the robot. Anthropometric traits that have been selected and taken into consideration within the simulation studies conducted were the height and the mass of the user. The aim of the studies conducted was to determine a relation between the height and the mass of the user and the obtained operational characteristics of the device. Conclusions drawn based on the work carried out are to make it possible to optimize, in the future, the control unit and to select the design solutions of the actuators with regard to an individual user, in order to minimize the electric energy consumed by the driving units of the robot.

2. Definition of the selected parameters

In the simulation model of the orthotic robot, there was a 16-member model of the human body implemented, which simulates the static and dynamic load of the device (Fig. 1). For the sake of simplification, it was assumed that the higher limbs are immovable and it was accepted that the body members are rigid bodies. Parameters of the simulation studies were the mass and the height of the user. Their changes result also in the changes of other mass-related parameters dependent on these two quantities, i.e. position of the centers of gravity, mass moments of inertia with respect to the three axes of the coordinate system as well as lengths of the successive segments of the body. Later in the text, presented is a way of determining values of these parameters for the purposes of the simulation studies.

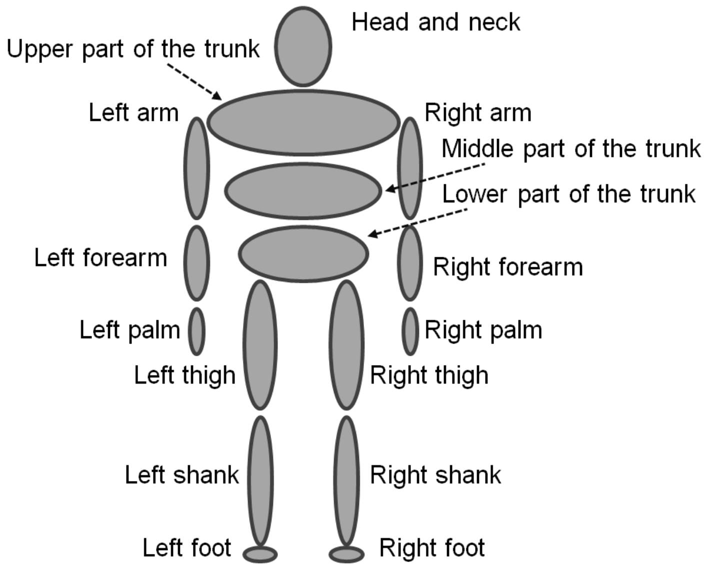

Fig. 1. Structure of the 16-member model of the human body

2.1. Masses of the body parts

Change of the total mass of the user or his height results in changes of the masses of particular segments of the 16-member model of the human body. According to [1], masses of the particular parts of the human body were computed using the following regression

$$m_i = A_{i1} + A_{i2} \cdot m_u + A_{i3} \cdot h_u \qquad i = 1...16\,, \tag{1}$$

where: m_i – mass of i-th body part [kg], m_u – mass of the user's body [kg], h_u – length of the user's body [cm], A_{i1}, A_{i2}, A_{i3} – regression coefficients [1].

2.2. Lengths of the body parts

Lengths of the body parts are determined as a function of one variable only, which is the height of the user. According to [9], lengths of particular parts of the human body were computed as fractions of the total height as illustrated in Fig. 2.

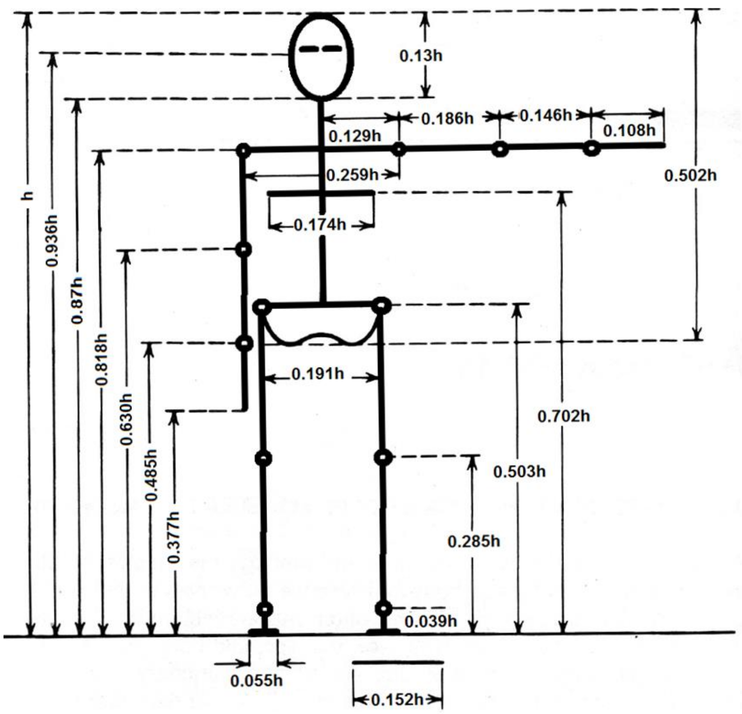

Fig. 2. Lengths of the body segments as a fraction of the body height *h*, according to [9]

2.3. Radius of the centers of gravity

It was assumed that the centers of gravity cover the long axis of a given segment, which results in the fact that in order to determine the position of the gravity center, it is sufficient to know one dimension only, namely the distance from the proximal end of a given body part. According to [1], positions of the gravity centers of particular parts of the human body were computed using the following equation

$$r_i = \frac{C_{i1} + C_{i2} \cdot m_u + C_{i3} \cdot h_u}{100} \qquad i = 1...16, \tag{2}$$

where: r_i – radius vector of *i*-th body part with respect to the proximal end of a given segment [m], C_{i1}, C_{i2}, C_{i3} – regression coefficients [1].

2.4. Mass moments of inertia

The central mass moments of inertia determine the way of mass distribution of an element around a given axis [1]. That results in a necessity of determining their values with respect to all three axes of the coordinate system. Using a regression would allow these values to be dependent on the mass and the height of the user, and then to be introduced in a matrix form into the blocks of the model

$$\mathbf{I}_i = \begin{bmatrix} L_{i0} + L_{i1} \cdot m_u + L_{i2} \cdot h_u & 0 & 0 \\ 0 & M_{i0} + M_{i1} \cdot m_u + M_{i2} \cdot h_u & 0 \\ 0 & 0 & N_{i0} + N_{i1} \cdot m_u + N_{i2} \cdot h_u \end{bmatrix} \quad i = 1...16, \qquad (3)$$

where: $\mathbf{I}_i$ – matrix of mass moments of inertia of i-th body part [kgcm^2], L_{i0}, L_{i1}, L_{i2}, M_{i0}, M_{i1}, M_{i2}, N_{i0}, N_{i1}, N_{i2}, – coefficients selected from respective tables for each body part [1].

3. Simulation model

Simulation model of the orthotic robot has been created using the Simulik/SimMechanics program under the Matlab environment. Its basic structure comprises a model of the loads that must be transmitted during the gait by the actuators, a model of the contact with the environment, a model of maintaining the vertical position during the gait and models of the actuators (Fig. 3). Additionally, the model employs courses of the gait patterns of healthy individuals, approximated using Fourier series, which are the set value for angular positions in particular articulations of the lower limbs of the user.

The model of loads comprises a model of the robot structure and the user's body, which because of their masses and a necessity of accelerating them during the gait, are a source of the static and dynamic loads with respect to the actuators. The model of the robot was created based on the existing technical model presented in [6].

Models of the actuators were created using the Simulink program. They make it possible to apply torques and forces within the driven articulations of the device, in such a way as to realize a set angular profile in the user's joints. For the purposes of the present studies, a mathematical model of the drive unit was used, which was applied in the technical model of the robot [5]. It consists of the following models representing a DC motor, a PID controller, as well as a flexible connector drive, a ball screw gear and a synchronous belt drive.

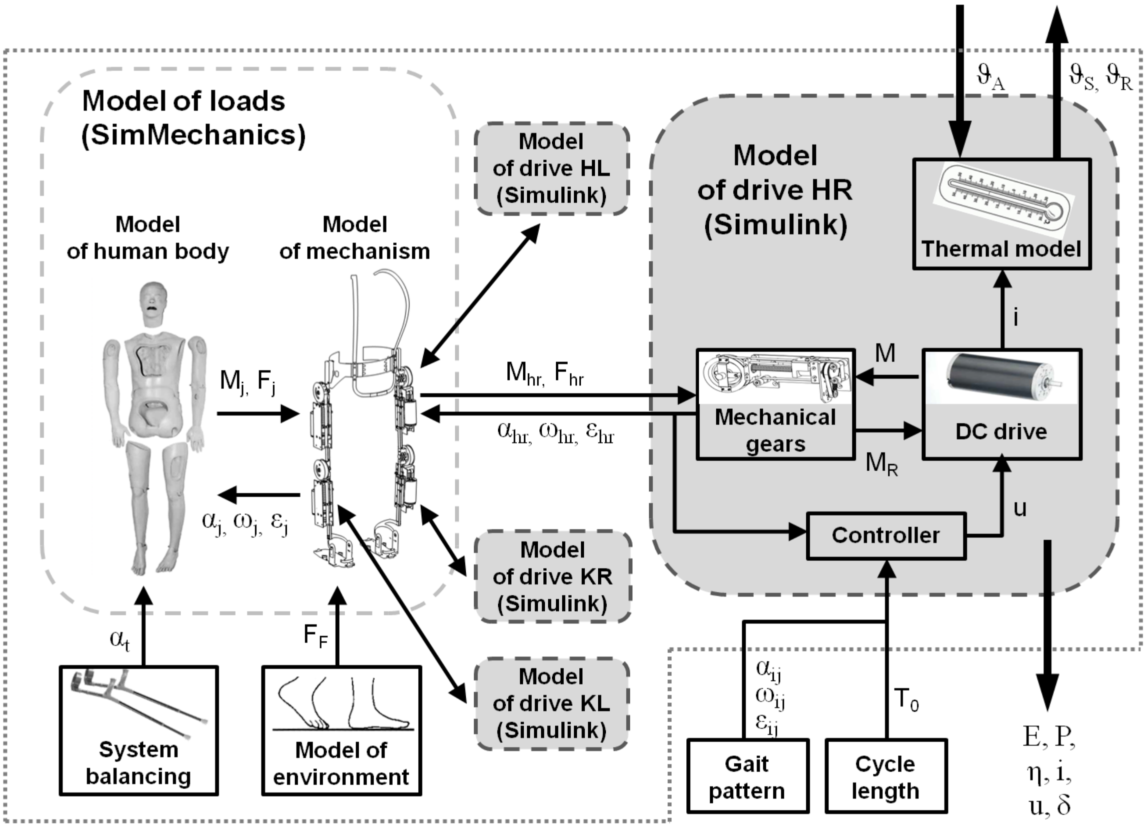

Fig. 3. Schematics of the simulation model

4. Simulation tests

Using the created simulation model the time courses were recorded of the basic mechanical values making it possible to specify requirements set for particular actuators. The respective quantities were: angular velocity in the articulation ω_j and the torque loading of this articulation M_j. Then, an instantaneous mechanical power was computed as follows

$$P_j = M_j \cdot \omega_j . \quad (4)$$

If the signs of the velocity and the torque are consistent, then we deal with motor operation (positive power), whereas if the signs of the torque and the velocity differ, the motor is driven by the external forces both static (resulting from the weight of the driven limbs) as well as dynamic. Then, the motor operates as generator and a negative power corresponds to these fragments of the graph. Within the current work, as far as the discussed studies are concerned, the actuators of the knee and hip articulations were chosen within the range of the motor operation. An exemplary course of the mechanical power required during the gait of a user having the mass of m_u=80 kg and the height of h_u=1.7 m are presented in Fig. 4 with regard to the knee and the hip articulation.

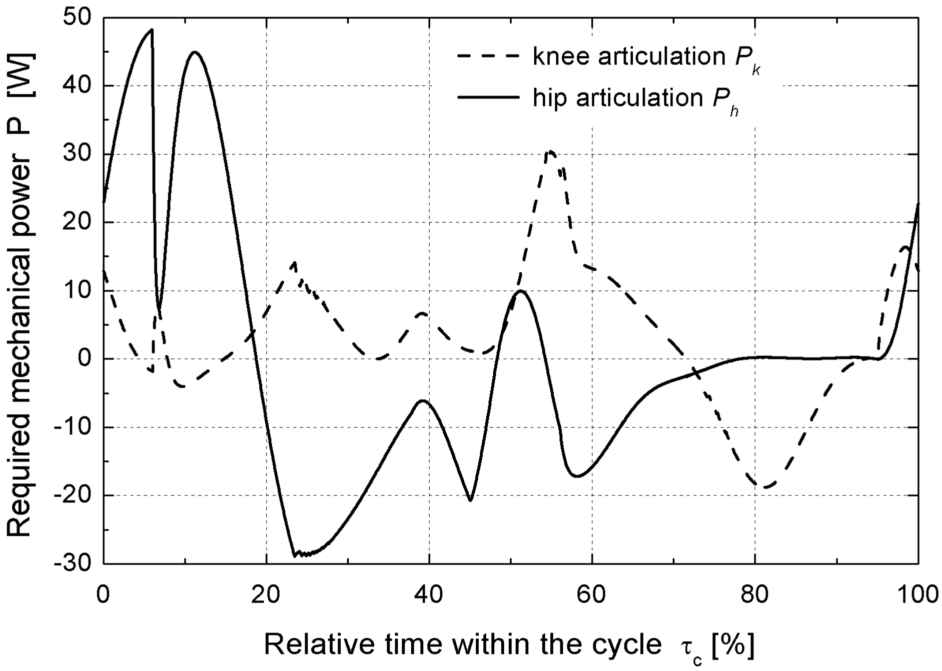

Fig. 4. Courses of the required mechanical power in the knee and the hip articulation for a gait with a step length of l_s=0.46 m and period T_0=3.8 s

The electric energy input E_t of the drive units of the four articulations within a single gait cycle is computed according to equation (5)

, (5)

where: i_j – current input of the motor of j-th articulation [A], u_j – control voltage of the motor of j-th articulation [V], E_t – total electric energy input of the motors of the driven articulations [J], T_0 – period of the gait cycle [s].

The simulation experiments were conducted which relied on realizing the same gait patterns along a distance of l_0 = 10 m and at a constant gait velocity υ_0 = 0.5 m/s for users having various masses and heights. Changing the user's height while keeping the same angular profiles in the joints, results in a change of the length of the performed steps. Thus, in order to keep a constant velocity of the gait it was accepted that the period of the gait cycle would be variable proportionally to the height of the user. During the simulation studies the mass of the user was changed within the range m_u = [60; 110] kg, and the height of the user was changed within the range h_u = [1.6; 2.0] m. The lengths of the steps were obtained within the range l_s = [0.46; 0.57] m and periods of the gait cycle T_0 = [1.84; 2.28] s. The results obtained of the simulation studies on energy consumption by the driving units as the function of the mass and the height of the user are presented in a graph (Fig. 5). Increase of the energy consumption rises significantly as the mass of the user increases. Changing the height of the user has much lesser influence on the quantity of the consumed energy. In the case of users having a small mass, i.e. below 80 kg, increasing the user's height is almost negligible since it does not cause an increase of the energy consumption larger than 3.5%. In the case of a user having a mass of 100 kg, increase of the height results in an increase of the energy consumption even by 15%.

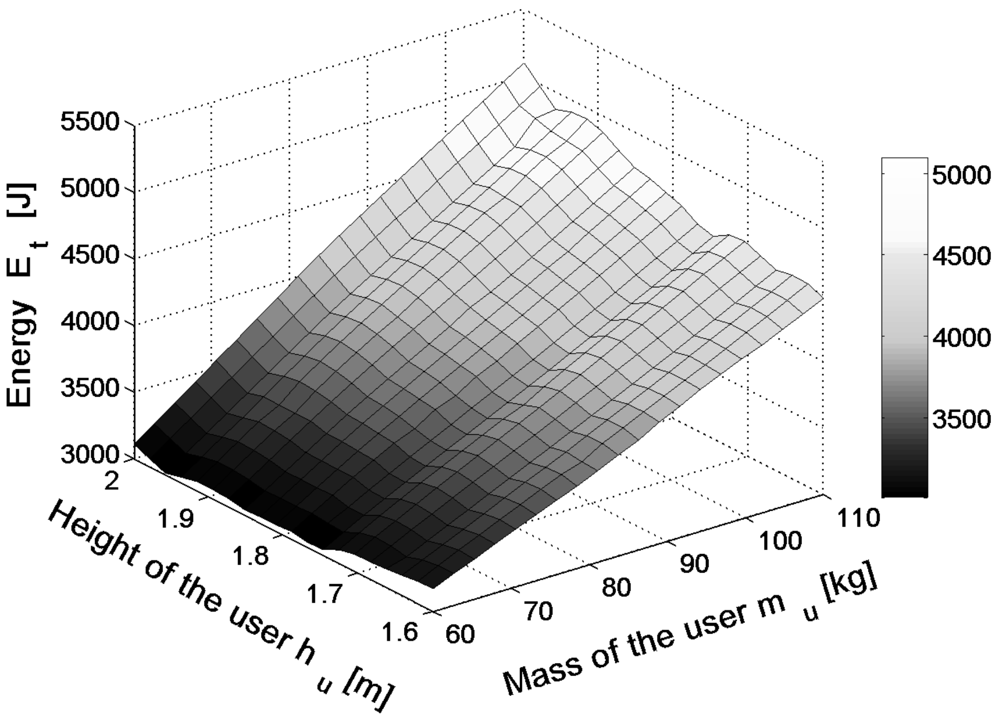

Fig. 5. Graph of the energy consumed by the drives of the hip and the knee articulation during a gait along the distance of l_0 = 10 m at the velocity of υ_0 = 0.5 m/s

5. Summary

Results of the simulation studies presented in the paper confirm the expectations concerning an increase of the energy consumption due to increase of the mass and the height of the user. However, so far, there has been no access to numerical values that would allow to determine how the energy consumption would change due to the changes of the individual traits of the user. Additionally, the studies conducted revealed that the energy consumption by the drive units of the orthotic robot does not linearly depend on the changes of the mass and height of the user. Further studies will be aimed at providing an answer to a question, how much energy can be saved by selecting parameters of the drive units individually for a user having specific anthropometric traits.

Acknowledgements

This article was financed from the ECO-Mobility project WND-POIG.01.03.01-14-154/09. The project was co-financed from the European Regional Development Fund within the framework of Operational Programme Innovative Economy.

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