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A Control Strategy for a Lower Limb Exoskeleton with a Toe Joint

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Outline of the presentation

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Motivation

The number of medical procedures with the use of robots in the US and Europe increased by 40% annually, which reduces the number of complications by 80%, significantly reduce the time of hospitalization, patients recover faster in the working process and ensure high quality of life

In the world

500 000 spinal injuries annually

6 000 000 stroke disease every year

400 000 000 people in wheelchairs

Basic methods of rehabilitation

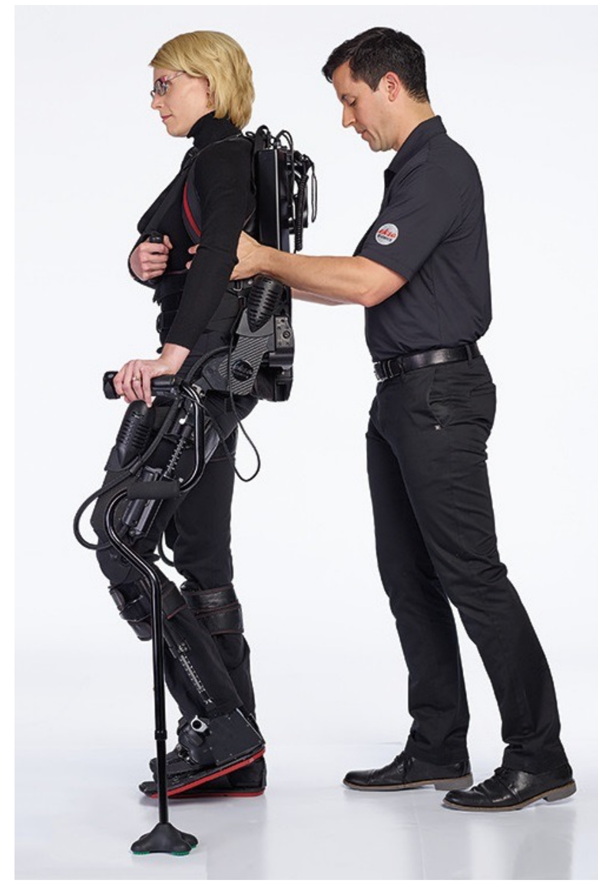
Simple low-efficiency mechanical verticalizers without walk function

Walking function is only implemented at stationary mechanotherapy complexes Hocoma (by Locomat), available only in 30 hospitals in the Russian Federation due to the very high cost of procurement

Assistive exoskeletons

RexBionics (New Zealand)

ExoAtlet (Russia)



Ekso Bionics (USA)

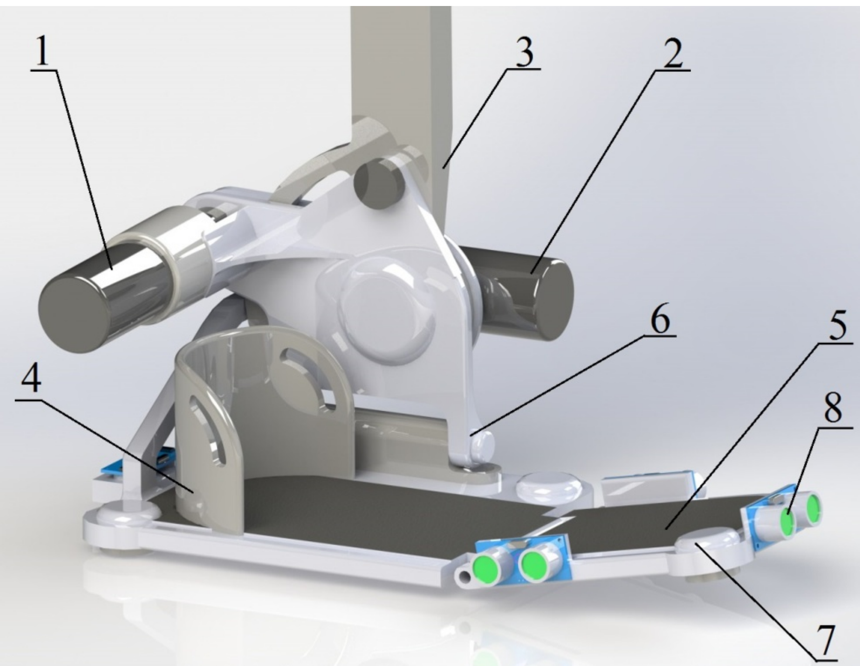
Problems

- Current research done in the area of exoskeletons focuses mostly on walking, while not giving enough attention to standing up motion.
- Dynamic balancing still remains an important problem for two-legged robotics in general and lower-limb exoskeletons in particular especially for non-crutches solutions.
- Dynamical analysis of verticalization process of patient usually is considered without reference on the problem of separation the heel from supporting surface. It changes square of supporting surface and require very precise control adaptive algoritm.
- Problem of the synthesis of an adaptive control system with an ability to correct its own control strategy based on the user's individual peculiarities still remains insufficiently studied.

Active foot of the ExoLite exoskeleton

An active toe joint can be used to achieve a number of goals:

1. To improve vertical balance of the system.
2. To train the feet muscles.
3. To allow the user to reach higher places than he would normally be able to.
4. To achieve more natural and energy-efficient gait.



1,2 – electric motors, 3 – exoskeleton's shin link, 4 – heel's support, 5 – exoskeleton's foot, 6 – framework for the motors, 7 – pressure sensors, 8 – distance sensors

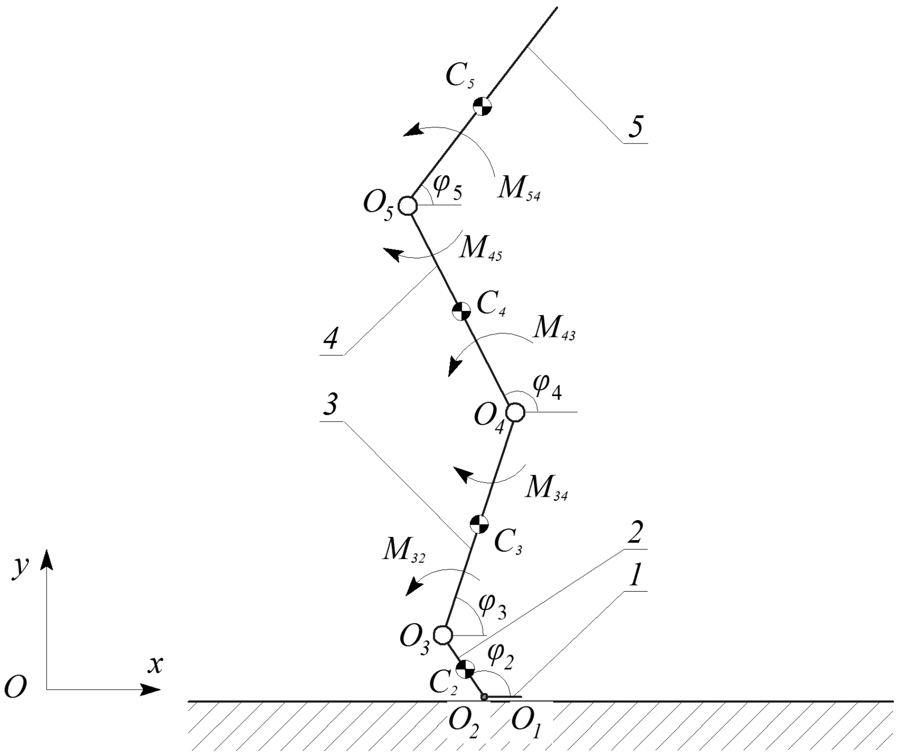
There are several modifications of the ExoLite's active foot:

The basic version includes pressure sensors and accelerometers.

The second tier version additionally includes distance sensors.

The last version is **«Flexisble foot»** which is made of flexible composite material, allowing the foot to slightly deform during the motion for better contact with the ground.

Analytical diagram of the exoskeleton during sit-to-stand motion



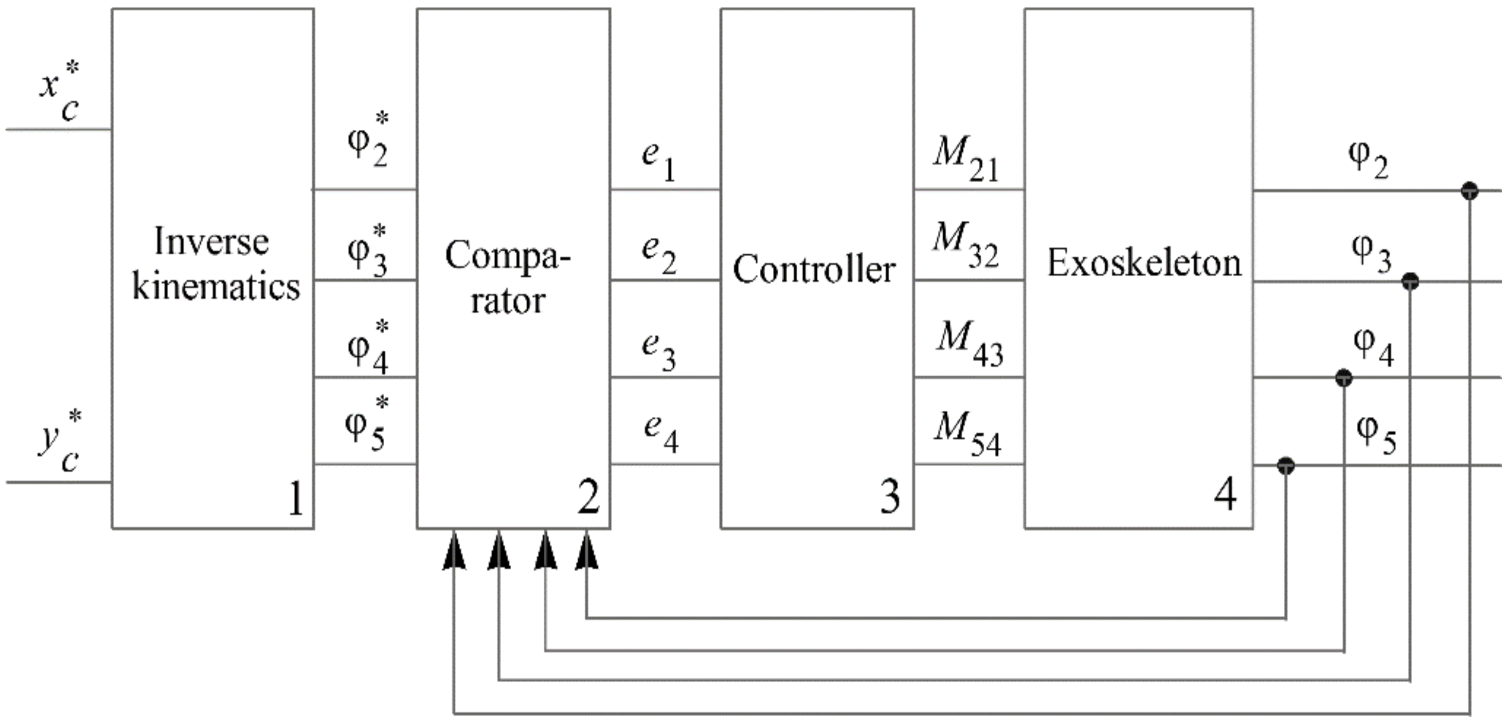
Scheme of the exoskeleton
in the sit-to-stand with reference on separation of heel of foot

Assumptions:

- Motion occurs only in a sagittal plane.
- The legs move symmetrically and synchronously
- The mass of each link is equally distributed along it's length
- Foot is fixed on ground and doesn't slip or slide

Points O_2, O_3 and O_4 - hinges, point O_1 is the exoskeleton's "toe". Points C_i - centres of mass of the mechanism's links. Angles φ_i define the orientation of the links with respect to the horizontal plane. The electric drives apply torques $M_{i,j-1}$ on the links

Control System design



Mathematical model

For further derivations we introduce a vector of generalized coordinates $\mathbf{q}$:

$$\mathbf{q} = \begin{bmatrix} \varphi_2 & \varphi_3 & \varphi_4 & \varphi_5 \end{bmatrix}^{\mathrm{T}} \tag{1}$$

It is possible to describe the system with only four generalized coordinates because of the assumption that the toe link remains motionless at all times during the verticalization process. The equations of motion of the system are given in vector form in the following way:

$$\mathbf{A}(\mathbf{q})\ddot{\mathbf{q}} + \mathbf{C}(\mathbf{q},\dot{\mathbf{q}}) + \mathbf{G}(\mathbf{q}) + \mathbf{\Phi}(\dot{\mathbf{q}}) = \mathbf{BM} \, , \tag{2}$$

where $\mathbf{A}(\mathbf{q})$ is a joint space inertia matrix, $\mathbf{C}(\mathbf{q},\dot{\mathbf{q}})$ is a vector of generalized Coriolis and normal inertial forces, $\mathbf{G}(\mathbf{q})$ is a vector of generalized potential forces, $\mathbf{\Phi}(\dot{\mathbf{q}})$ is a vector of generalized dissipative forces, $\mathbf{M}$ is a vector of motor torques, and $\mathbf{B}$ is a linear operator that transforms the vector of motor torques into the vector of the generalized forces. Algorithms for calculating the mentioned vectors and matrices, as well as detailed discussion of their properties can be found in [19].

Description of the control system diagram

In the control system diagram x_C^* and y_C^* are the desired coordinates of the center of mass, φ_i^* are the desired values of the generalized coordinates and e_i^* are components of the control error vector:

$$\mathbf{e} = \begin{bmatrix} e_2 & e_3 & e_4 & e_5 \end{bmatrix}^{\mathrm{T}} = \mathbf{q} - \mathbf{q}^*, \tag{3}$$

where $\mathbf{q}^*$ is the vector of the desired values of the generalized coordinates, defined in the same way as $\mathbf{q}$. The values of x_C^* and y_C^* can be found using ZMP control methodology (as it was done in [17]) or directly given by polynomial functions, as it was done in [6, 18]. Here we will consider the later case.

The control actions of the regulator are given by the following equation:

$$\mathbf{M} = \mathbf{B}^{-1}\mathbf{A}\left(\ddot{\mathbf{q}}^* + \mathbf{K}_p\mathbf{e} + \mathbf{K}_d\dot{\mathbf{e}}\right), \tag{4}$$

where $\mathbf{K}_p$ and $\mathbf{K}_d$ are diagonal gain matrices with positive elements. The derivation of this controller and the discussion of its properties can be found in [19]. The general theory of such feedback controllers is presented in [20]. The method of tuning the gain matrices $\mathbf{K}_p$ and $\mathbf{K}_d$ is given in paper [21].

The decision on whether or not the toe joint should be engaged is made based upon how close the mechanism is to a singular position. To measure how close the mechanism is to a singular position we introduce the following matrix $\mathbf{J}$:

$$\mathbf{J} = \frac{\partial \mathbf{r}_{C5}}{\partial \mathbf{q}} \left(\frac{\partial \mathbf{r}_{C5}}{\partial \mathbf{q}} \right)^{\mathrm{T}}, \tag{5}$$

where $\mathbf{r}_{C5}$ is the radius vector that describe the position of the center of mass of the torso link of the robot. The matrix $\mathbf{J}$ is a square two by two, and it becomes singular when the mechanism enters a singular position. Its condition number $\kappa(\mathbf{J})$ gets larger as the mechanism approaches a singular position, which allows us to use it as an indicator.

$$\mathbf{J} = \begin{bmatrix} l_1 s_2^2 + l_2 s_3^2 + l_3 s_4^2 + l_4 s_5^2 & -l_1^2 s_2 c_2 - l_2^2 s_3 c_3 - l_3^2 s_4 c_4 - l_4^2 s_5 c_5 \\ -l_1^2 s_2 c_2 - l_2^2 s_3 c_3 - l_3^2 s_4 c_4 - l_4^2 s_5 c_5 & l_1 c_2^2 + l_2 c_3^2 + l_3 c_4^2 + l_4 c_5^2 \end{bmatrix},$$

where $s_2 = \sin(q_2)$, $s_3 = \sin(q_3)$, $s_4 = \sin(q_4)$, $s_5 = \sin(q_5)$,

$c_2 = \cos(q_2)$, $c_3 = \cos(q_3)$, $c_4 = \cos(q_4)$, $c_5 = \cos(q_5)$.

The condition number $\kappa(\mathbf{J})$ can be calculated using the following formula:

$$\kappa(\mathbf{J}) = \|\mathbf{J}\| \cdot \left\|\mathbf{J}^{-1}\right\|, \tag{6}$$

where $\|\cdot\|$ is a matrix norm. Here we consider Euclidean matrix norm, which means that $\|\mathbf{J}\| = \sigma_{\max}$, where $\sigma_{\max}$ is the maximum singular value of the matrix $\mathbf{J}$. Singular values can be obtained via singular value decomposition (SVD). The value of $\sigma_{\max}$ can also be found as a square root of the largest eigenvalue $\lambda_{\max}$ of the matrix $\mathbf{J}^{\mathrm{T}}\mathbf{J}$. The eigenvalues of $\mathbf{J}^{\mathrm{T}}\mathbf{J}$ are in turn found using the following equation:

$$\left|\mathbf{J}^{\mathrm{T}}\mathbf{J} - \lambda\mathbf{I}\right| = 0, \tag{7}$$

where $\mathbf{I}$ is an identity matrix:

$$\mathbf{I} = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix},$$

In the case of $\mathbf{J}$ being a two by two matrix $\mathbf{J}^{\mathrm{T}}\mathbf{J}$ is also a two by two matrix, hence the equation (7) can be rewritten as a second order quadratic equation that has two solutions. The square root of the largest solution of the equation (7) then gives us $\sigma_{\max}$.

The work of the algorithm during the first stage can be described as follows:

$$\begin{cases} \varphi_2 = \pi \quad if \quad \kappa(\mathbf{J}) < \kappa_{\max} \\ \alpha_1 \le \varphi_2 \le \pi \quad if \quad \kappa(\mathbf{J}) \ge \kappa_{\max} \end{cases}, \tag{8}$$

where:

α_1 - is a constant that defines the restriction in the range of motion of the toe joint.

$\kappa_{\max}$ - is a threshold value for the condition number of $\mathbf{J}$. If $\kappa > \kappa_{\max}$ then the matrix $\mathbf{J}$ is close enough to being degenerate, which means that the toe joint needs to be activated. The physical meaning of $\kappa_{\max}$ is that it determines how much the body of the exoskeleton can unbend before the toe will become activated. A low value of $\kappa_{\max}$ will lead to the toe to be almost always active, while high level of $\kappa_{\max}$ would result in toe being activated only when eh exoskeleton can't reach further without it.

There are also additional constraints placed on the decision variables. These constraints are there because the human body has restricted ranges of motion in the joints:

$$\alpha_2 \le \varphi_3 - \varphi_2 \le \alpha_3,\ \alpha_4 \le \varphi_4 - \varphi_3 \le \alpha_5,\ \alpha_6 \le \varphi_5 - \varphi_4 \le \alpha_7, \tag{9}$$

where α_i are the constants that determine the range of possible motions in the joints of the exoskeleton user. They can be either individually measured using standard procedures or obtained from the literature [24]. Relations (7) and (8) form the set of constraints for the optimization problem.

On the second stage the proposed algorithm minimizes the following objective function:

$$J_1(\mathbf{q},t) = \left\| \mathbf{r}_C(\mathbf{q}) - \mathbf{r}_C^*(t) \right\| . \tag{10}$$

It should be noted that the objective function (9) depends on time, which reflects the iterative nature of the algorithm – it needs to be run for every point of time where a solution of the inverse kinematics problem is needed.

The formula for the desired joint space trajectories $\mathbf{q}^*(t)$ obtained by the algorithm has the following form:

$$\mathbf{q}^*(t) = \underset{\mathbf{q}}{\arg\min}\, J_1(\mathbf{q},t) . \tag{11}$$

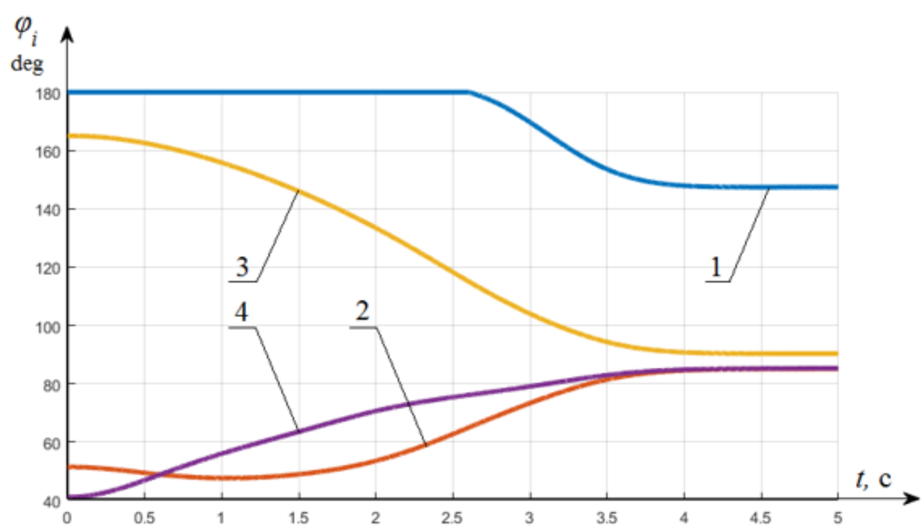
The resulting desired joint space trajectories $\mathbf{q}^*(t)$ are smoothed by an averaging filter before being used as inputs for the control system.

Numerical simulation

The goal of the numerical simulation is to study the controlled motion of the robot in the sit-to-stand regime. Using the equations of motion (2) we can solve the following three tasks:

1. Calculate the joint torques that are needed to realize a given trajectory of the robot.
2. Calculate the trajectory of the robot for given joint torques (open loop control).
3. Calculate the trajectory of the robot for a given feedback controller (closed loop control).

Here the third problem is considered. In next figure the time functions of the generalized coordinates are shown,



The time functions of the generalized coordinates; 1 – $\varphi_2(t)$, 2 – $\varphi_3(t)$, 3 – $\varphi_4(t)$, 4 – $\varphi_5(t)$

We can observe the graph $\varphi_2(t)$ shown in fig. 3 Behave similar to a piece-wise polynomial function. For $t < 2.89$ s $\varphi_2(t) = 180$ degrees, and after that it over the next two seconds it monotonically decreases till it reaches the value of 147.5 degrees. We can show that the time t_c at which the graph $\varphi_2(t)$ starts to decrease depends on the chosen value of $\kappa_{\max}$. This is illustrated on the next slide.

Study of toe angle range

Because the angle φ_2 can not exceed π, then its range is defined by the minimal value it can assume during the motion of the exoskeleton. As it was shown in the previous slides the value of φ_2 is decreasing monotonically or remains constant, therefore the final value of φ_2 is also its minimal value (for the type of motion that is being considered in this study).

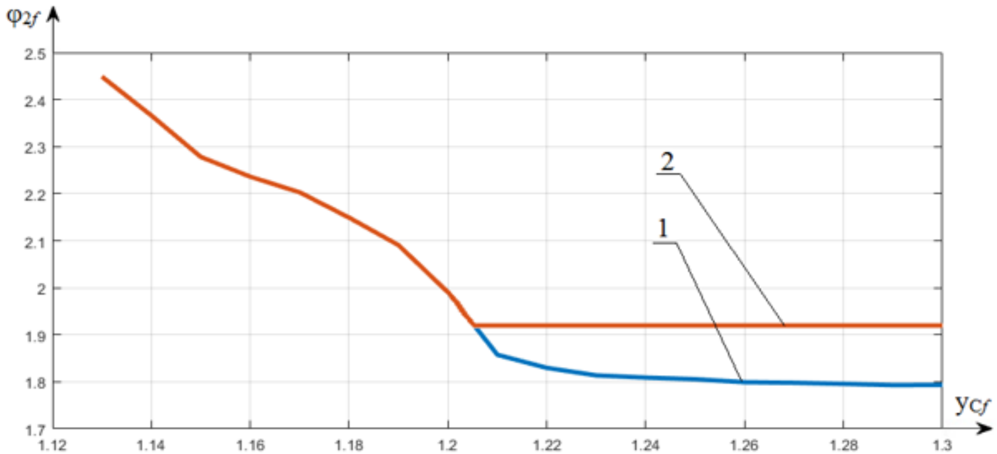
It is possible to demonstrate that the final value of φ_2 is a function of the final value of y_C^* - the desired height of the center of mass. We introduce the following notation:

t_f - the duration of the motion.

$\varphi_{2,f}$ - the **final value** of φ_2 angle, $\varphi_{2,f} = \varphi_2(t_f)$.

$y_{C,f}$ - the **final value** of desired height of the center of mass y_C^*, $\varphi_{2,f} = \varphi_2(t_f)$.

In figure below the dependence of $\varphi_{2,f}$ on $y_{C,f}$ is shown.

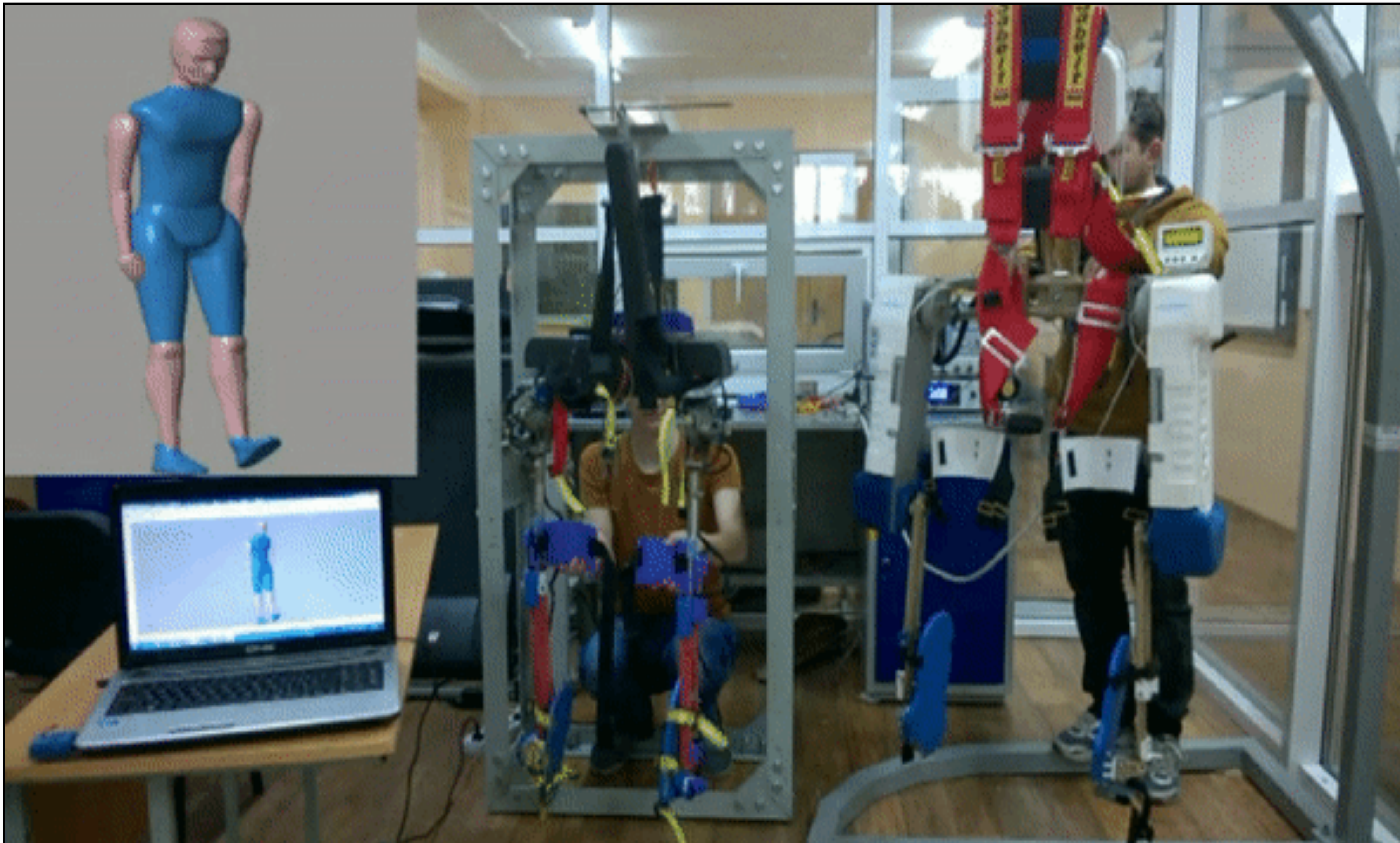


1 – dependence that does not take into account the physiological restrictions of toe angle range; 2 – dependence that take into account those restrictions

Fig. The dependence of $\varphi_{2,f}$ on $y_{C,f}$

The graph on figure above shows that it is possible to control the range of change of the foot angle by setting the value of $y_{C,f}$. The dependence can also be used to obtain the maximum value of center of mass elevation for the exoskeleton user, with regard to their individual range of motions in the toe joint.

Laboratory set up



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Experimental prototype of the lower-limb exoskeleton

EXO LITE

ExoLite – lower limb powered exoskeleton, designed to increase functionality by providing mobility for people with damage musculoskeletal system.

The capabilities of the exoskeleton:
Stable Walking on a horizontal surface;
Individual anthropomorphic design;
Verticalization without crutches;
Climbing on stairs;

Time Autonomous work up to 4 hours;
Designed for a user weighing up to 70 kg and weight from 1.6 to 1.9 meters.

Conclusions

1.In this paper a lower limb exoskeleton with a toe joint was considered. A mathematical model of the exoskeleton was presented, and the equations of motion were given.

2. Control system based on a feedback controller was proposed. The inputs for the control system were generated by defining a desired trajectory of the center of mass of the mechanism and solving the inverse kinematics problem.

3. Numerical optimization-based iterative algorithm for solving inverse kinematics was proposed.

4. The algorithm allows to engage and disengage the toe joint, based on how close the mechanism is to a singular position. That gives us an automatic human-like toe joint engagement, that can be controlled though certain parameters that were discussed in the fourth chapter of the paper.

Acknowledgements and Future work

The work is done with support of the **Russian Scientific Foundation**, project №14-39-00008.

Future work on the project includes:

- Extensive modeling of exoskeleton motion in realistic environment in 3d space.
- Designing control system for exoskeleton capable of operating in in-door and out-door environment without endangering or overstraining the patient.
- Conducting experimental study of exoskeleton's controlled motion when performing different tasks and exercises.

Thank you for attention!

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