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Admittance Control of an Industrial Robot during Resistance Training

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Abstract: Neuromuscular strength training of the leg extensor muscles plays an important role in the rehabilitation and prevention of age and wealth related diseases. In this paper, we focus on the design and implementation of a Cartesian admittance control scheme for isotonic training, i.e. leg extension and flexion against a predefined weight. For preliminary testing and validation of the designed algorithm an experimental research and development platform consisting of an industrial robot and a force plate mounted at its end-effector has been used. Linear, diagonal and arbitrary two-dimensional motion trajectories with different weights for the leg extension and flexion part are applied. The proposed algorithm is easily adaptable to trajectories consisting of arbitrary six-dimensional poses and allows the implementation of individualized trajectories.

Keywords: Assistive Technology and Rehabilitation Engineering, Human-Computer Interaction, Automatic control

1. INTRODUCTION

Regular training offers a high potential for the prevention and therapy of e.g. age-related cognitive decline and neurodegenerative diseases (Bherer et al., 2013). According to this, resistance training is not only advisable for young and healthy but also for older people or patients suffering from traumatic sport injuries or arthrosis (Williams and Stewart, 2009; McAlindon et al., 2014). An effective training requires high muscle forces. These induce high loads on already impaired structures potentially leading to training-induced injuries. To ensure an effective but also safe training, the training device should be able to measure and control the forces applied to the musculoskeletal system. In addition, also the corresponding velocities along the motion trajectory and the range of motion are determining factors and require permanent monitoring.

Today's conventional training devices allow such a controlled movement execution e.g. the leg press machine of *exerbotics*. Chen et al. (1993) present an overview of available devices for knee extension and flexion. However, different muscular activations can exert a reaction force with the same magnitude and direction as stated by Jacobs and van Ingen Schenau (1992). This yields the assumption, that for the estimation of joint loadings the force alone is not sufficient. Previous results show, that a setup consisting of a diagonal leg press, a force plate, a motion capturing system and a musculoskeletal model enables the estimation of joint loadings (Kolditz et al., 2015). According to this, an experimental research platform consisting of an industrial robot and a force plate mounted at the end-effector has been set up at the German Sport University in Cologne. In contrast to a conventional leg press, the industrial robot allows for arbitrary six-dimensional motion trajectories yielding the possibility to realize specific movements both in position and orientation. Also variable loads along the motion trajectory e.g. different weights during extension and flexion can be applied addressing the variations in knee extension and flexion strength (Harbo et al., 2012). Akdoğan and Adli (2011) and Meng et al. (2015) review different rehabilitation robots including their control strategies for the lower limbs and organize them in e.g. exoskeletons and end-effector based ones. There exist several different end-effector based systems like foot plates based ones (Schmidt et al., 2007; Hesse et al., 2012) to simulate gait and platform based devices (Girone et al., 2001; Saglia et al., 2013) for ankle rehabilitation. In this case, high loads are induced by the robot to improve coordination and muscle strength of the lower limbs. To the best of author's knowledge, a comparable system for the neuromuscular training of the lower limbs is currently not available on the market and the development and implementation of an isotonic training scenario has not been addressed in the literature yet.

For this purpose, an admittance control scheme is considered, which uses a virtual dynamics model to determine the robot's motion based on the force applied by the patient (Whitney, 1977; Newman, 1992). In contrast to an impedance controller, it imposes position or velocity and the external force applied, serves as controller input. For an overview of different forms of human-robot inter-

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action and existing robot force control algorithms refer to Goodrich et al. (2008) and Zeng and Hemami (1997), respectively. Keemink et al. (2018) present admittance control as method of physical interaction between humans and robots. There exist several different admittance control schemes of robots for the rehabilitation of lower limbs e.g specifically for knee recovery (Wang et al., 2009), gait (Bortole et al., 2013) and ankle rehabilitation (Saglia et al., 2010). This paper deals with the development and implementation of an isotonic training scenario, e.g. the leg extension training with an industrial robot against a constant weight using an admittance control scheme.

This paper is structured as follows. Section 2 deals with isotonic training implementation. In this context different parts such as the trajectory planning, the basic behavior model as well as specific model extensions are considered. The experimental setup and the different test scenarios are described in Section 3 and the corresponding results are analyzed in Section 4. Finally the conclusions are drawn in Section 5.

2. ISOTONIC TRAINING IMPLEMENTATION

Resistance training also called weight training or strength training represents an exercise that requires the body's musculature to move against a constant weight. There exist two different setups of conventional leg press machines. In the first setup the patient sits on a movable seat and applies a force to a non-moving foot plate. In the second setup however, the patient sits on a non-moving seat and applies a force to a movable foot plate. The machine can be loaded with weight plates, while modern training equipment allows for the definition of a counter force which is then generated by electrical motors. In contrast to a conventional leg press, in the predefined setup the force is induced by an industrial robot, which moves the force plate mounted at its end-effector according to the measured force vector. Therefore, an admittance control scheme is used, which consists of the following steps:

(1) Trajectory planning in Cartesian space with support poses $\mathbf{x} = (x, y, z, a, b, c)^T$ for the robot's end effector
(2) Definition of the trajectory variable s as the way along the trajectory
(3) Calculation of the acceleration $a = \ddot{s}$ of the force plate resulting from the applied force according to model of virtual system dynamics by the admittance controller
(4) Limitation of the acceleration
(5) Integration of the acceleration to the velocity $v = \dot{s}$ along the trajectory
(6) Limitation of the resulting velocity
(7) Integration of the velocity to calculate the resulting position on the trajectory
(8) Mapping of the current velocity and position on the trajectory to the corresponding velocity and pose of the robot's end effector in Cartesian space

2.1 Trajectory planning

As a basic isokinematic training trajectory, the trajectory for resistance training consists of a leg extension and flexion part (Kolditz et al., 2016; Ketelhut et al., 2018). The robot allows for arbitrary six-dimensional poses in Cartesian space yielding the possibility for the definition of patient specific trajectories defined by support poses.The poses between the support poses are interpolated linearly, i.e. it is important to define enough poses for a smooth trajectory. Once this trajectory is planned in Cartesian space, the one-dimensional variable s as the way along the trajectory is introduced. The constant resistive force, that can be defined separately for the extension and flexion part, as well as the external force applied by the patient serve as inputs for the admittance controller, which outputs the acceleration along the trajectory.

2.2 Admittance Controller

As stated before, the admittance control scheme aims at changing the set-point to a low-level motion controller through virtual model dynamics based on the external force applied by the patient (Keemink et al., 2018). The complete Cartesian admittance control loop is shown in Fig. 1. Assuming an underlying internal motion controller of the robot, the virtual system dynamics defined to mimic the behavior of a real leg press during resistance training read

$$m \cdot a = F_{ext} - F_{res} - F_f \ , \tag{1}$$

where m is the virtual mass of the weights applied, a the acceleration along the way and F_{ext}, F_{res} and F_f the external, resistive and friction forces, respectively. According to this, in the case of an ideal leg press without friction forces, the patient's opposing force only depends on the weight applied.

As described by Van Geffen (2009), the most simple friction models consist of Coulomb, viscous and static friction. However, in reality the friction usually decreases with increasing velocity. The model, which describes this behavior is called Stribeck friction model. As long as the sliding speed of the interacting surfaces is equal to zero, only static friction or stiction is present. If the external force F_{ext} exceeds the static friction force F_S, motion is initiated. There exist various different variants of Stribeck friction. A general form is given by

$$F_f = \left[F_C + (F_S - F_C) \mathrm{e}^{-\left(\frac{|v|}{v_s}\right)^{\delta}} \right] \ sign(v) \ , \tag{2}$$

where F_C and v are the Coulomb sliding friction force and the sliding speed (Akmeliawati et al., 2011; Andersson et al., 2007). The constants $\delta = 2$ and $v_s = 0.002$ m/s are an empirical parameter that determines the shape of the model and the Stribeck sliding speed coefficient, respectively.

The Coulomb sliding friction force

$$F_C = \mu_{\mathrm{H}} \ F_{\mathrm{N}} \tag{3}$$

as well as the static friction force

$$F_S = \mu_{\mathrm{S}} \ F_{\mathrm{N}} \tag{4}$$

are proportional to the normal load F_{N} times the static $\mu_{\mathrm{H}} = 0.2$ and sliding friction coefficient $\mu_{\mathrm{S}} = 0.1$ of steel.

2.3 Robot Specific Safety Features

In order to guarantee a soft motion stop at the start- and endpoint of the trajectory, both velocity and acceleration are limited. The velocity at both points has to be zero,

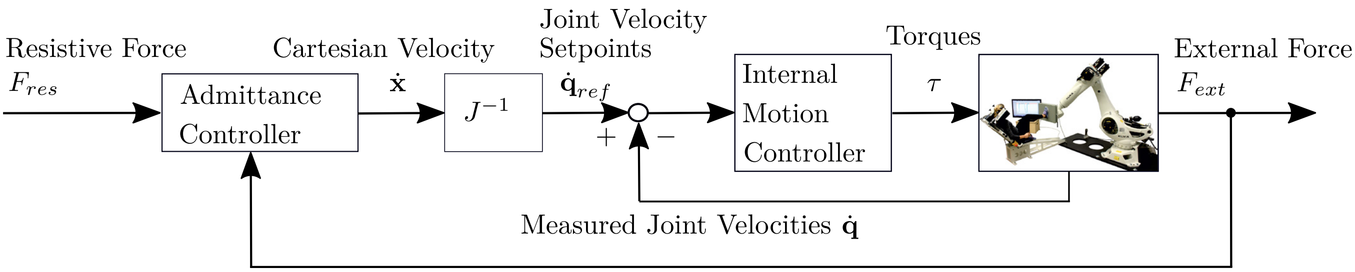

Fig. 1. Cartesian admittance control loop of an industrial robot during resistance training.

which leads together with the two position conditions to at least four constraints on the trajectory, which have to be fulfilled (Sciavicco and Siciliano, 2012; Craig, 2005). For this reason, a polynomial of at least third order is required. In this case, the acceleration has a linear profile with initial and final discontinuity though. If the initial and final acceleration have to be addressed too, a polynomial of higher order is required. On the robotic training system the acceleration as well as the deceleration function is defined as fourth order polynomial for the way s

$$s(t) = c_4t^4 + c_3t^3 + c_2t^2 + c_1t + c_0 \quad (5)$$

from and towards the end points of the trajectory, yielding third and second order polynomials for velocity and acceleration, respectively. Setting the start time to $t_{start} = 0$, the required deceleration time t_d from this position s_{start} towards the end of the trajectory s_{end} is calculated to $t_d = 2\,(s_{end} - s_{start})/\,v_{start}$ with the starting velocity v_{start}. The remaining unknown coefficients c_0 to c_4 are calculated with the initial and final conditions $s(0) = s_s$, $s(t_d) = s_{end}$, $v(0) = v_{start}$, $v(t_{end}) = v_{end}$ and $a(0) = a(t_{end}) = 0$.

After remapping the way s and the velocity v to the corresponding Cartesian values of $\mathbf{x}$ and $\dot{\mathbf{x}}$, the resulting joint velocities $\dot{\mathbf{q}}_{ref}$ for the internal motion controller are determined with the Moore-Penrose pseudoinverse of the Jacobian

$$\dot{\mathbf{q}}_{ref} = \mathbf{J}^{+}\dot{\mathbf{x}} \quad (6)$$

based on the Denavit Hartenberg parameters of the robot, see Fig. 1. Without further constraints regarding the maximum velocity and acceleration, high joint velocities would be reached, yielding high Cartesian velocities and accelerations. In reality, the high payload industrial robot is in direct interaction with patients. Thus high velocities and accelerations might endanger them. According to this, workspace limitations and boundaries for the Cartesian acceleration and velocity have to be defined. Fig. 2 shows the simulated Cartesian coordinates of a horizontal isotonic leg extension training trajectory with acceleration (a_{max} =0.1 m/s^2) and velocity (v_{max} =0.07 m/s) boundaries and the corresponding joint velocities for constant external and resistive forces of F_{ext} =590 N and F_{res} =490 N. The first two plots (top and middle) show the Cartesian position in y- and z-direction and the way s, velocity v and acceleration a along the trajectory. The third plot (bottom) displays the corresponding joint velocities. The results illustrate, that neither the maximal acceleration nor the maximal velocity boundary is exceeded during the trajectory. During the deceleration phase though, minimal accelerations up to -0.2 m/s^2 are reached. In this phase however, a predefined deceleration function is used to obtain a fast motion stop.

3. EXPERIMENTAL SETUP

The experimental setup consists of an industrial robot with a payload of 270 kg (KR270 R2700 ultra, KUKA AG, Augsburg, Germany) and a 3D force plate (AMTI, Watertown, USA). The robot allows maximum flexibility in applying arbitrary motion trajectories. The force plate, which is mounted at the end effector of the robot, captures force and torque data.

For preliminary testing and validation of the designed admittance controller for the isotonic training, three different experiments are performed on the robotic research platform. Therefore, a (I) horizontal, (II) diagonal and (III)

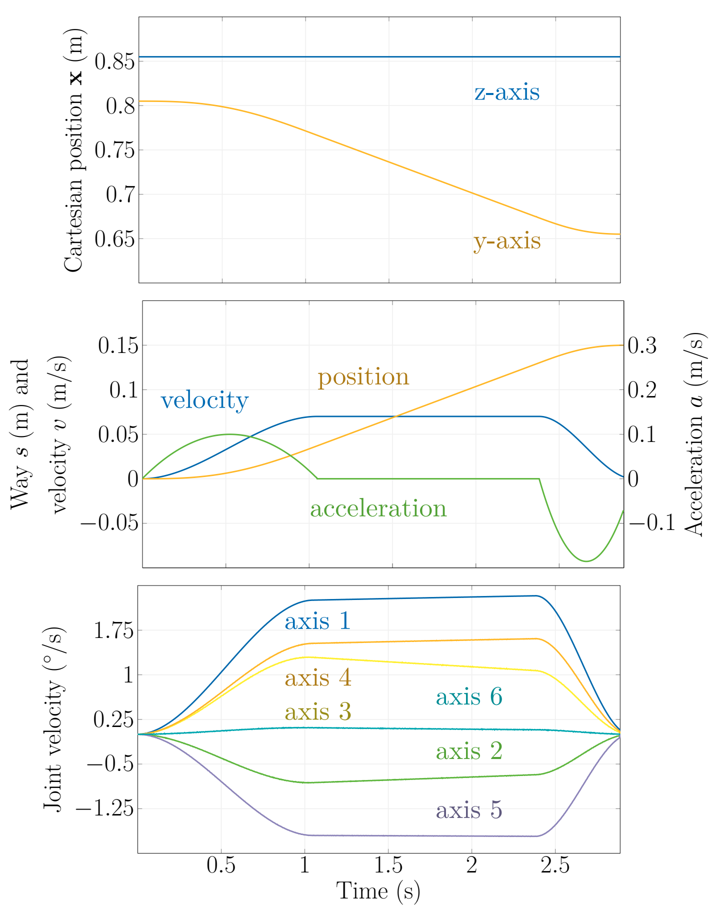

Fig. 2. Simulated Cartesian coordinates in y- and z-direction (top) of a horizontal isotonic leg extension training trajectory (I) with acceleration and velocity boundaries and a length of 15 cm as well as the corresponding joint velocities (bottom).

arbitrary two-dimensional motion trajectory and variable weights during leg extension and flexion are used. The corresponding trajectories are shown in Fig. 2 (top) to Fig. 4.

(I) The first experiment consists of a horizontal motion trajectory with a length of 15 cm. In this case, the plate only moves in y-direction, i.e. back and forth during leg extension and flexion.

(II) The second experiment deals with a diagonal motion trajectory as shown in Fig. 3. In this case, not only the Cartesian position in y-direction but also in z-direction is varied in order to model a diagonal motion trajectory as in a conventional leg press.

(III) Finally, an arbitrary two-dimensional motion training is done. The corresponding trajectory is shown in Fig. 4. The aim of this experiment is to illustrate the flexibility of the designed algorithm regarding arbitrary six-dimensional motion trajectories.

The admittance control scheme including the model of virtual system dynamics described in Section 2.2 with the safety features described in Section 2.3 is used. In this case, the high payload industrial robot is in direct interaction with the patient. Therefore, additional restrictions regarding the robot's velocity and acceleration are considered to ensure safety. In the following three experiments, acceleration and velocity are limited to 0.1 m/s^2 and 0.07 m/s.

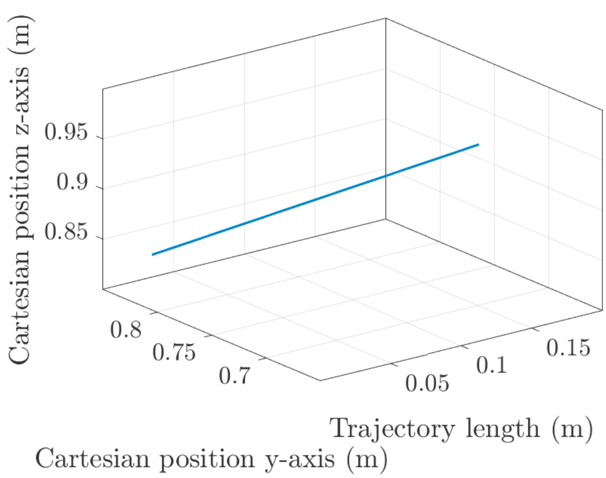

Fig. 3. Diagonal motion trajectory (II).

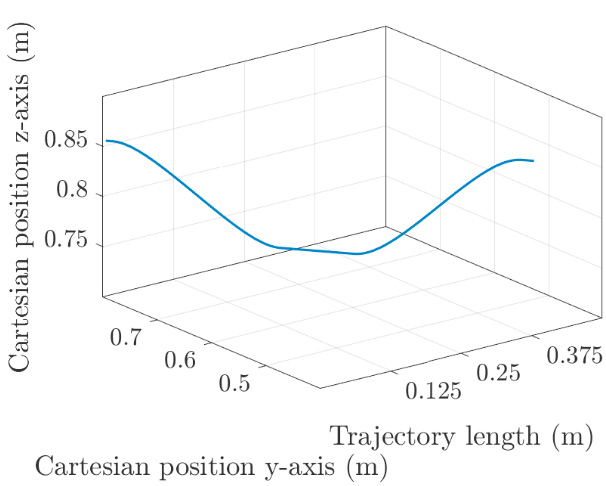

Fig. 4. Two-dimensional trajectory (III) in Cartesian space.

4. RESULTS AND DISCUSSION

The three different motion trajectories described in Section 3 are applied on the robotic research platform to test and validate the designed isotonic training algorithm.

The aim of the first experiment is to test if the designed Cartesian admittance control algorithm is able to mimic (I) horizontal isotonic training with an industrial robot. The corresponding results are shown in Fig. 5. For the force applied by the patient refer to the first plot (top). The corresponding Cartesian coordinates in y- and z-direction and joint velocities can be found in the two plots below (middle and bottom). If the force applied by the patient F_{ext} is higher than the opposing force consisting of resistive F_{res} and friction force F_f, the robot moves backwards. As soon as the force is taken away though, the opposing force drives the plate backwards to the start position. If the external force exactly outweighs

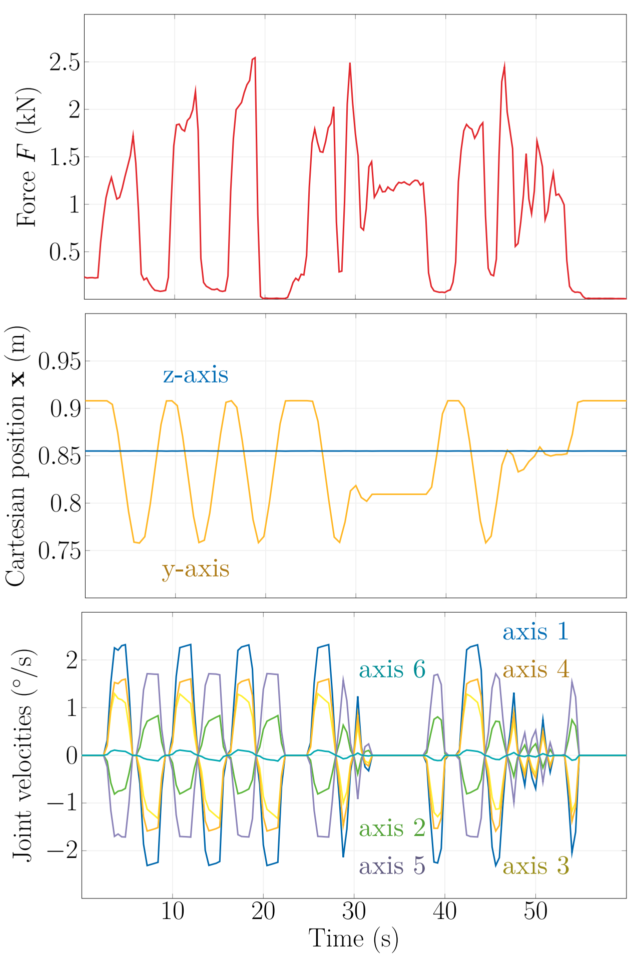

Fig. 5. External force (top), Cartesian coordinates in y- and z-direction (middle) and corresponding joint velocities (bottom) of the robotic research platform during the (I) horizontal isotonic leg extension training.

the opposing force, the virtual weights are stabilized at any point along the trajectory, see Fig. 5 within the range of 32 s to 36 s. Furthermore, the joint velocities are comparable to the results of the simulation shown in Fig. 2 and thus demonstrate that the restrictions regarding the Cartesian velocity and acceleration are fulfilled. During extension and flexion constant weights of 100 kg and 120 kg are applied. Therefore, the patient uses two legs to push the force plate away by straightening of the legs.

As stated before, the second experiment deals with a (II) two-dimensional diagonal trajectory. The force applied and the resulting Cartesian coordinates in y- and z-direction and joint velocities are shown in Fig. 6. The weights are reduced to 50 kg and 75 kg during extension and flexion yielding one-legged workout. As a result, the force applied by the patient is considerably smaller compared to the first experiment. Nevertheless, the results show a similar system behavior, even though also a plate movement in z-direction is executed. Apart from that, in the middle of the trajectory no steady state can be reached.

Finally, for the results of the (III) arbitrary two-dimensional motion trajectory, i.e. force, resulting Cartesian coordinates in y- and z-direction and joint velocities, refer to Fig. 7. Again weights of 50 kg and 75 kg are induced by the robot. Even though the trajectory is much longer compared to the first two experiments, the algorithm is able to obtain quite similar results, which fulfill the requirements.

5. CONCLUSION

The development and implementation of an admittance control scheme for the isotonic training, i.e. the leg extension and flexion against a constant weight has been considered. For this purpose, a model of the desired virtual system dynamics was designed to mimic the behavior of a real leg press. To test and validate the designed algorithm for isotonic training, three different experiments are performed as a linear, diagonal and an arbitrary two-dimensional motion trajectory and different weights during leg extension and flexion are applied. The results illustrate that the admittance controller is able to mimic the behavior of a real leg press during isotonic training while robotic specific safety features are met. Furthermore, the scheme is easily adaptable to trajectories consisting of arbitrary six-dimensional poses in Cartesian space. According to this, the setup allows the optimization and implementa-

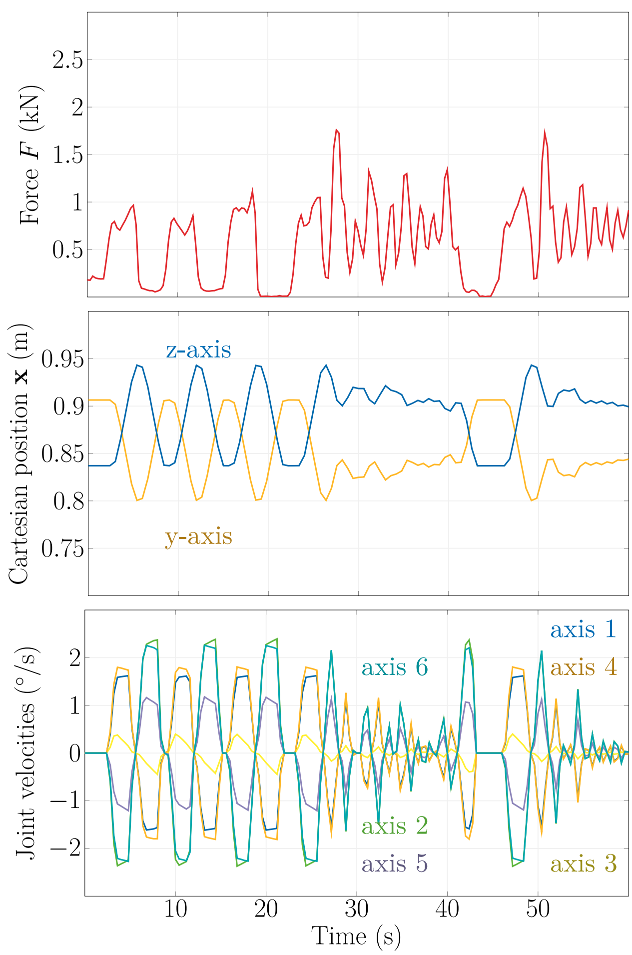

Fig. 6. External force (top), Cartesian coordinates in y- and z-direction (middle) and corresponding joint velocities (bottom) of the robotic research platform during the (II) diagonal isotonic leg extension training trajectory.

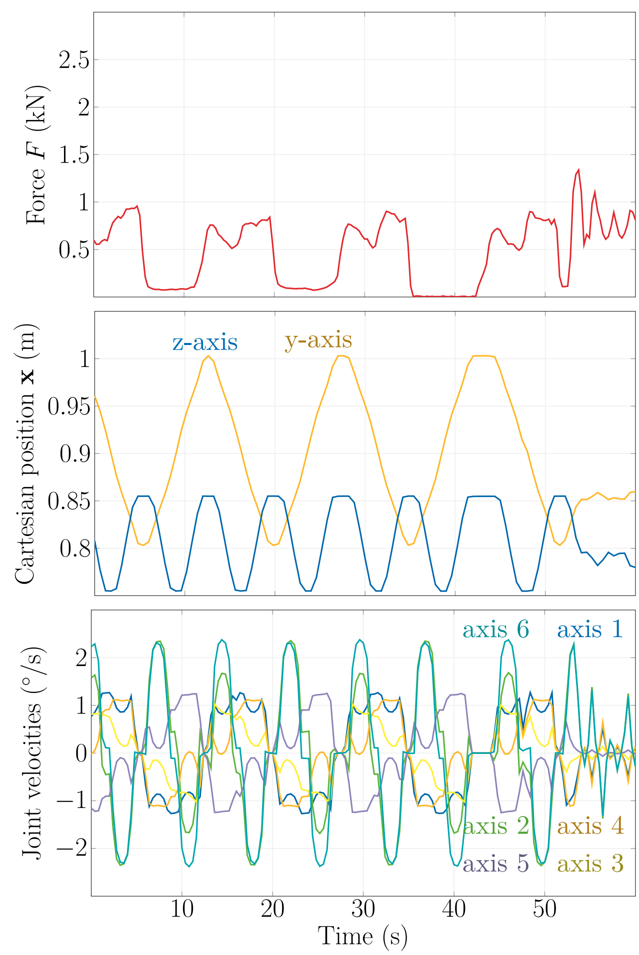

Fig. 7. External force (top), Cartesian coordinates in y- and z-direction (middle) and corresponding joint velocities (bottom) of the robotic research platform during the (III) arbitrary two-dimensional isotonic leg extension training trajectory.

tion of specific individualized trajectories. In combination with a motion capturing system and inverse kinematic and dynamic calculations on musculoskeletal models also joint loadings such as the knee adduction moment can be estimated. Based on these estimations a control algorithm to minimize knee joint loadings shall be designed in order to improve the training for elderly and impaired people.

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