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Comparison of Different Training Algorithms for the Leg Extension Training with an Industrial Robot

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Abstract: In the past, different training scenarios have been developed and implemented on robotic research platforms, but no systematic analysis and comparison have been done so far. This paper deals with the comparison of an isokinematic (motion with constant velocity) and an isotonic (motion against constant weight) training algorithm. Both algorithms are designed for a robotic research platform consisting of a 3D force plate and a high payload industrial robot, which allows leg extension training with arbitrary six-dimensional motion trajectories. In the isokinematic as well as the isotonic training algorithm, individual paths are defined in Cartesian space by sufficient support poses. In the isotonic training scenario, the trajectory is adapted to the measured force as the robot should only move along the trajectory as long as the force applied by the user exceeds a minimum threshold. In the isotonic training scenario however, the robot's acceleration is a function of the force applied by the user. To validate these findings, a simulative experiment with a simple linear trajectory is performed. For this purpose, the same force path is applied in both training scenarios. The results illustrate that the algorithms differ in the force dependent trajectory adaption.

Keywords: Rehabilitation Technology and Prosthetics, Surgical Navigation and Robotics.

1 Introduction

Resistance training is an effective method to prevent and treat chronic diseases and can enhance the physical and mental health of healthy as well as patients suffering from sport injuries or other diseases [1]. To overcome the disadvantages and limitations of current training devices, a research and development training platform consisting of an industrial robot and a 3D force plate has been developed [3]. In previous work, an isokinematic (motion with constant velocity) leg extension and flexion training scenario have been designed and implemented in *MATLAB/Simulink* [2]. The focus of this paper lies on the comparison with an isotonic (motion against constant weight) leg extension and flexion training scenario and the identification of differences and potential development opportunities.

2 Training Scenarios

Both training scenarios consist of a leg extension and flexion part. During the isokinematic training, the foot plate moves with a constant velocity back and forth along a force triggered trajectory [2]. Whereas in the isotonic training, the acceleration of the foot plate is based on the force applied by the patient as well as the resistive force induced by the robot. Both training algorithms are described in the following, starting with the path planning in Cartesian space, followed by the trajectory planning part, which endows the path with time information and adapts it based on the force applied. Finally, the corresponding joint velocities are calculated.

Path Planning in Cartesian Space

In the isokinematic as well as the isotonic training scenario different variable motion paths can be used. In contrast to a conventional leg press, the robot allows for an arbitrary six-dimensional pose of the robot's end effector

$$\mathbf{x} = (x, y, z, a, b, c)^T \tag{1}$$

in Cartesian space. Paths are defined with sufficient support poses $\mathbf{x}_i$ to ensure a smooth motion. Fig. 1 shows the start and

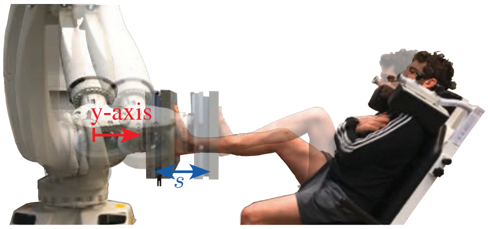

Fig. 1: Start and end position of linear path with a length of $15\,\mathrm{cm}$ during leg extension training and the way along the trajectory s.

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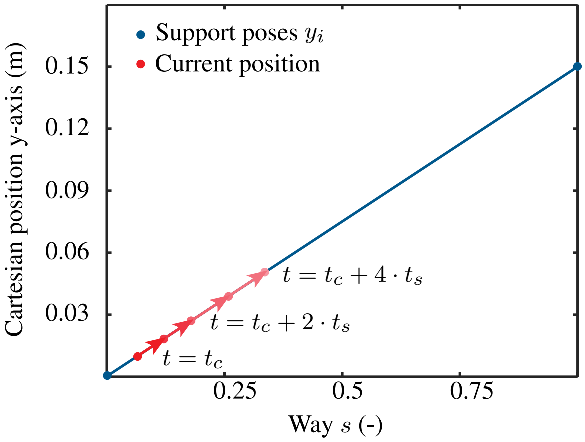

Fig. 2: Linear Cartesian path with three support poses (blue) and the variable s moving along the path with current time t_c and sample time t_s.

end pose of a linear trajectory with a length of $15\,\mathrm{cm}$ during leg extension training. The robot only moves in y-direction, i.e. back and forth during leg extension and flexion. To realize the motion depicted in Fig. 1, at least the two support poses shown in Fig. 2 are required. The one-dimensional variable s describes the way along the path. If the current position lies in between two support poses, they are interpolated linearly, i.e. the variable s moves along the path based on the force applied by the patient. The force dependent trajectory adaption in both algorithms is described in the following.

Force dependent Trajectory Adaption

In the isokinematic training scenario, a triggered trajectory is used, i.e. as soon as a minimal force is induced by the patient a movement with constant velocity along the path is initiated [2]. As the Cartesian velocity at the start and end of the trajectory are zero, the force plate accelerates first, followed by a phase with constant maximum velocity and finally decelerates again. In the acceleration and deceleration phase, a polynomial of fourth order is used to describe the way s yielding third and second order polynomials for the corresponding velocity v and acceleration a.

In the isotonic training scenario, the force applied by the patient and the resistive force serve as inputs for a mechanical model which outputs the acceleration of the force plate. The corresponding velocity and position are determined by the integration of the acceleration along the trajectory. As in the isokinematic training scenario an acceleration and deceleration function with a fourth order polynomial for the way s is used during deceleration. In this case, the industrial robot with a payload of $270\,\mathrm{kg}$ is in direct interaction with the patient. To address this issue in the isotonic training scenario, additional restrictions regarding the robot's acceleration and velocity are considered. Acceleration and velocity are limited to a maximum amount of $0.1\,\mathrm{m/s^2}$ and $0.07\,\mathrm{m/s}$ respectively. Apart from that, very small accelerations are inhibited.

In both algorithms, the resulting position s and velocity v are mapped on the path in Cartesian space as shown in Fig. 2 to determine the corresponding pose $\mathbf{x}$ and velocity $\dot{\mathbf{x}}$ of the robot's end effector in Cartesian space.

Trajectory Planning in Joint Space

Finally, the corresponding joint velocities $\dot{\mathbf{q}}$ are calculated with the Moore-Penrose pseudoinverse $\mathbf{J}^+$ of the Jacobian [2].

3 Results and Discussion

In order to validate the findings of Section 2, a simulative experiments with a simple linear trajectory with a length of $15\,\mathrm{cm}$ is done. During extension and flexion, weights of $50\,\mathrm{kg}$ and $75\,\mathrm{kg}$ are taken into account in the isokinematic as well as the isotonic training scenario. As stated before, in both algorithms variable six-dimensional trajectories with sufficient support poses can be defined in Cartesian space. During both training scenarios, these trajectories are adapted based on the force applied. To test the force dependent trajectory adaption of both algorithms, the force shown in Fig. 3 is applied.

The corresponding results of the isotonic as well as the isokinematic (dashed) training algorithm are shown in Fig. 4. For the Cartesian coordinates refer to the first plot and for the way s and velocity v along the trajectory as well as the corresponding joint velocities to the two plots below respectively. The results of the isokinematic training scenario illustrate that the force plate moves back and forth along the trajectory as long as the minimal weight force limit is exceeded. Otherwise, the force plate keeps its position until motion is triggered again, e.g. in the time range $3\,\mathrm{s}$ till $8\,\mathrm{s}$. Whereas in the isotonic

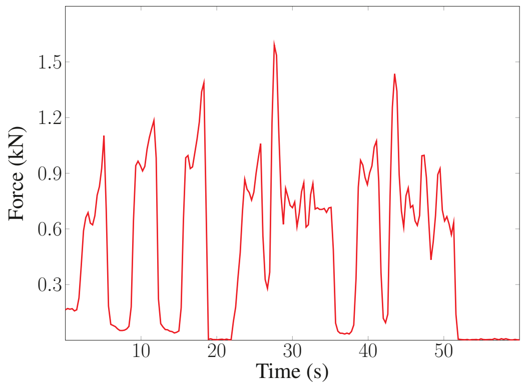

Fig. 3: Applied force during the simulated horizontal isotonic and isokinematic leg extension training.

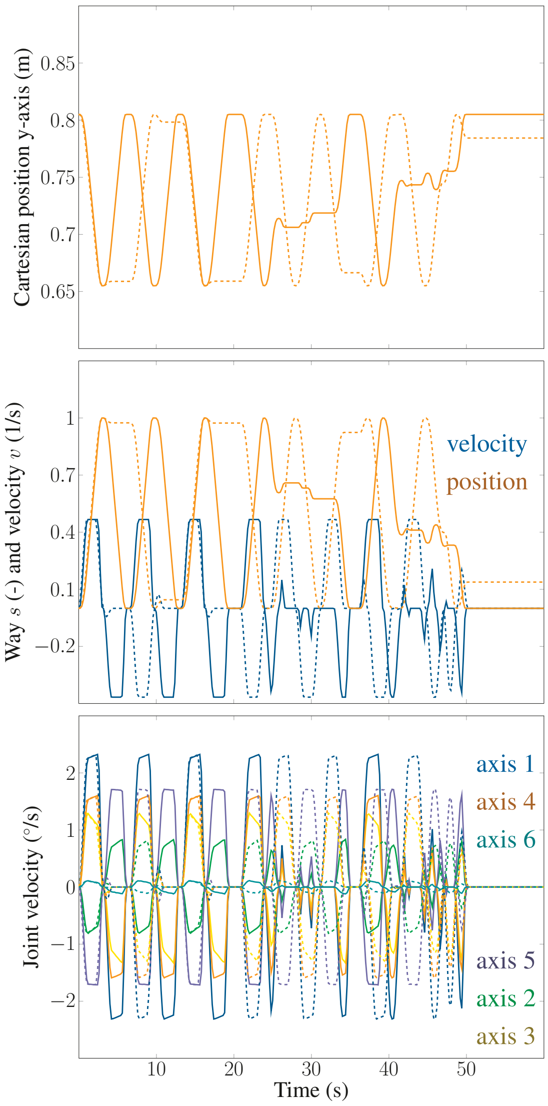

Fig. 4: Simulated Cartesian coordinate of y-axis (top), way s and velocity v along the linear trajectory (middle) and corresponding joint velocities (bottom) of the robotic research platform during the horizontal isotonic and isokinematic (dashed) leg extension training.

training scenario, the acceleration of the force plate is a function of the force applied. If the force outweighs the sum of resistive force and friction force, the position of the force plate is kept constant as shown at $t = 30\,\mathrm{s}$ in the middle of the trajectory. Otherwise, the plate also moves back and forth along the trajectory provided that the force applied is higher than the opposing force. If this is not the case, the resistive force drives the force plate back to its start position as in a conventional leg press machine.

4 Conclusion

In this paper, an isokinematic and an isotonic training algorithm on a robotic research platform, i.e. leg extension and flexion with a constant velocity and against constant weight, are compared. Both algorithms allow the definition of individualized paths in Cartesian space, which are adapted depending on the force applied. In the isokinematic training scenario a certain force limit has to be exceeded to initiate motion with constant velocity, while the acceleration in the isotonic training scenario depends on the force induced by the patient. The results show that the algorithms differ in the force dependent trajectory adaption. In combination with a motion capturing system and dynamic calculations on musculoskeletal models also joint loadings such as knee adduction moments can be estimated and incorporated in the motion control of the robot. Apart from this, extremes of knee extension and flexion have to be avoided as they yield to potentially damaging tibiofemoral shear forces and an increased patellar compression [4]. According to this, future work will focus on the implementation of knee angle limitations and control of knee adduction moments during training.

Author Statement

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