Using a Robotic Gait Orthosis as Haptic Display – A Perception-Based Optimization Approach

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Abstract—The actuated gait orthosis LOKOMAT has been developed at University Hospital Balgrist for patients with impairments due to neurological or orthopedic lesions. To enhance rehabilitation with the LOKOMAT, patient-cooperative techniques have been developed. Patient-cooperative means that the technical system considers the patient intention and efforts rather than imposing any predefined movement or inflexible strategy. It is hypothesized that patient-cooperative techniques have the potential to improve the therapeutic outcome compared to classical rehabilitation strategies.

One example for patient-cooperative techniques are immersive, multi-modal scenarios. They can provide task-specific feedback and are expected to increase patient’s motivation to contribute. One interaction possibility is haptic feedback which can be provided by the gait orthosis to simulate interaction with solid objects.

The work described here investigated the potential of the LOKOMAT to provide haptic feedback. Frequency response measurements under closed-loop conditions were conducted to determine the force and position bandwidths. The final goal was to develop an approach for haptic rendering and optimize its parameters with experiments. Optimization criteria were object hardness and stability during object contact.

Results of the bandwidth measurements show that the angle bandwidth is 3 Hz (excitation angle amplitude: 3°) and the force bandwidth 8 Hz (excitation force amplitude: 10 N). The implemented haptic approach combines an impulsive force component, a penalty force component, and a component for lateral friction force. Best results were achieved for a combination of sine shape impulse, spring constant $K$ with $2000 \text{Ns/m}$, and modified damping coefficient $B$ with $300 \text{Ns/m}^2$.

I. INTRODUCTION

A. Automated Treadmill Training

In the USA, about 10,000 new cases of spinal cord injury occur every year [1]. Much more people suffer from stroke, there are an estimated 5.7 million stroke survivors in the USA[1]. These kinds of injuries cause locomotor dysfunction, which can be partially or fully restored by motor rehabilitation.

One form of gait restoration is manual treadmill training [2], [3]. This rehabilitation method requires two or three physiotherapists, who move the patient’s legs, while they are in a sitting position. Because of the exhaustive character of this therapy for the therapists and the number of training sessions is limited. To automate treadmill training and thereby make life easier for therapists, the actuated gait orthosis LOKOMAT was developed at University Hospital Balgrist. The main advantage over manual treadmill training is that patients can train longer and more intensive than before. Other advantages are increased accuracy of the trained pattern and improved feedback possibilities for the patients.

The LOKOMAT is a robotic orthosis with two degrees of freedom per leg for hip and knee rotation (see Fig. 1). The system can be used to control a patient’s leg movement in the sagittal plane. Hip and knee joints are actuated by drives, which are built into an exoskeletal structure. In this structure, position and force sensors are integrated to provide input for the controller. The entire system is mounted on a treadmill. The patient’s weight is unloaded by a mechatronic system [4], allowing gradual increase of the body weight which has to be supported.

Most times in clinical use, the LOKOMAT is position-controlled, although slight variations of the predefined trajectory are allowed. Nevertheless, the patients are moved regardless of their own contribution. Thus, for many patients training is neither motivating nor challenging.

B. Virtual Environments for Rehabilitation and the Role of Haptics

To enhance motor rehabilitation and overcome mentioned deficits, virtual scenarios are widely investigated and used for motor rehabilitation [5], [6]. The goal is to provide an exciting environment, motivating patients to contribute significantly with arbitrary motor activity and train longer and more frequently.

When focusing on the role of haptics in virtual environments for motor rehabilitation, reviews agree on its importance [7], [8]. One review characterizes haptic information as an “effective addition towards the accomplishment of certain treatment objectives such as increasing joint range of motion and force” [9]. Therefore it is desirable to use the LOKOMAT as haptic display which generates forces to render solid objects.

C. Haptic Rendering and Validation

The term haptic rendering refers to the generation of forces in reaction to the user’s actions in a virtual world. The goal is to simulate haptic interaction with solid objects in a realistic way.
Haptic rendering can be done with a variety of algorithms, which differ in accuracy and computational effort. One rather advanced approach combines “impulsive forces upon contact and penalty and friction forces during contact” [10]. With this combination the perceived hardness at initial contact is implemented with impulsive forces, while resting contact perception is conveyed with penalty and friction forces.

To evaluate the ability of a given haptic display to render a solid object, frequency response measurements are an established method. For endeffector-based interaction devices high force bandwidths were achieved. 85 Hz are reported by Ellis et al. [11] and 70 Hz by Yoon and Ryu [12] for their respective devices. Exoskeleton devices do not perform in the same range, because they have larger inertia and transmit forces by a kinematic chain. Bandwidths for exoskeleton hand devices are reported at 10 Hz (RMII-ND Haptic Glove) and 40 Hz (CyberGlove with CyberGrasp) at fingertip [13]. For foot devices, mechanical bandwidths go down to 1.5 Hz for the Rutgers Dual Stewart Platform Mobility Simulator [14].

However, quantitative metrics as bandwidths, rate-hardness [15], and vibration amplitude are not sufficient to evaluate the performance of a haptic interaction device. From a user’s perspective, the perception of the three interaction stages

1) initial wall touch,
2) resting contact, and
3) cleanliness of release

can be distinguished and experimentally evaluated with questionnaires to gain subjective metrics. [16]

Apart from bandwidth measurements, one commonly used approach for tackling the issue of stability of haptic devices is passivity [17]. However, for the selected approach with nonlinear damping and an impulsive force component, passivity analysis is not straight-forward, since it relies on linearization.

D. Goal

The goal of the work presented here is to evaluate the potential of the LOKOMAT to provide haptic feedback in interactive, multi-modal training scenarios. A suitable approach for haptic force generation has to be selected, implemented, and optimized for a variety of solid objects.

II. METHODS

A. Impedance and Admittance Control

For the control of a haptic display the two complementary control architectures admittance control (see Figure 2a) and impedance control (see Figure 2b) exist [18]. The used parameters follow largely the conventions used by Volpe [19] and are defined as

\[ q \] joint angles of haptic device,  
\[ \tau \] torques,  
\[ x \] cartesian coordinates of haptic device,  
\[ Y_e \] admittance,  
\[ Z_e \] impedance,  
\[ J \] Jacobian matrix \( (\dot{x} = J(q) \cdot \dot{q}) \),  
\[ K_F \] force controller gain,  
\[ K_V \] velocity controller gain, and  
\[ jZ_{hd} \] dynamics of haptic display in joint space \( (\tau = jZ_{hd} \cdot \dot{q}) \).

For the subsequent discussion of which controller architecture to prefer, we have to be aware of the control tasks and types of simulated environment. In the experiments discussed here the orthosis is supposed to allow subjects as unimpeded walking as possible. This behaviour corresponds to a low or zero impedance of the simulated virtual environment. Whenever an obstacle is hit, walking is impeded for a short time due to haptic feedback. Since an obstacle is a rigid object of high inertia, a high impedance has to be simulated.
B. Discussion of Implemented Control Architecture

With these extreme requirements, none of the two architectures can provide stable and adequate rendering of all desired environment conditions. However, taking into consideration the expected short time of object collision, we decided to use an impedance control architecture also for the haptic feedback. It must be emphasized that for the desirable high object stiffness during collision, stability of the controller may not be given for all possible approaching velocities. The stability aspect will also be a major goal for parameter optimization.

For the experiments with healthy subjects, which are discussed here, the impedance control architecture is used. This control structure allows zero impedance while compensating the orthosis’ friction and gravity forces (model-feedforward) for unimpeded walking and high impedance for obstacle collisions.

The haptic implementation used in these experiments does not change the impedance \((Z_e)\) itself but is computed separately and added to \(\tau_c\). Collision with the foot tip is the only collision considered in this implementation, because it is most likely to occur for the task of obstacle crossing and considering the constraints (movement constraints due to the orthosis, low obstacles). Figure 3 shows forces and torques created or affected by haptic rendering. The computed haptic forces have either horizontal (impulsive and penalty forces) or vertical (friction force) direction, since the obstacle form is restricted to cubes. These two orthogonal force components are transformed to hip and knee torques using the Jacobian matrix \(J^T\). The three components impulsive force, penalty force, and friction force are discussed now in more detail.

1) Impulsive Force: When the subject’s foot tip penetrates into a virtual solid object, an impulsive force is generated once. The amplitude of this impulse \((\hat{F})\) depends on the velocities at object collision and on the type of collision (elastic, inelastic) [20] and can be computed with

\[
\hat{F} = 2 \frac{m_1 m_2}{m_1 + m_2} \cdot (v_1 - v_2) \cdot (1 + e) \cdot T_l,
\]

where \(m_1\) and \(v_1\) refer to the mass and velocity of the first object (the subject’s leg for the described case), \(m_2\) and \(v_2\) to the second object (the obstacle), and \(T_l\) denotes the impulse duration. The collision coefficient \(e\) depends on the materials that are involved and lies between 1 (elastic collision) and 0 (inelastic collision).

The shape of the impulse can be approximated by a
forward solution and can be noted as object. A linear spring damper system would be a straight-object surface) which drives the subject's foot out of the object by generating an inversely directed force (perpendicular to the concept of haptic feedback is to punish object penetration

\[ F_P = -Kx_1 - B^* \ddot{x}_1, \]  

where \( F_P \) represents the penalty force, \( x_1 \) the penetration depth, \( \dot{x}_1 \) the penetration velocity, \( K \) the spring constant, and \( B^* \) the damping coefficient. However, the demand for clean release can not be satisfied with this approach, since the force could be nonzero at the object border. To avoid force discontinuities at object release, a modified spring damper approach is used, with

\[ F_P = -Kx_1 - Bx_1 \dot{x}_1, \]  

where \( B \) represents the modified damping coefficient. Note that \( B \) has a different unit ([\( B^* \)] = \( \text{Ns/m}^2 \), \([B] = \text{Ns/m}\)).

3) Friction Force: When touching a wall, friction forces act parallel to the object surface and inhibit vertical movement of the touching member (subject’s foot). Using a modified Coulomb model with penalty force \( F_P \) results in

\[ F_F = \begin{cases} \mu \cdot F_P \cdot \frac{v_u}{|v_u|} & \text{if } |v_u| > |v_{thr}| \\ \mu \cdot F_P \cdot \frac{v_u}{v_{thr}} & \text{else} \end{cases}, \]

with \( F_F \) being the friction force, \( v_u \) the velocity in vertical direction, \( v_{thr} \) the friction threshold velocity, and \( \mu \) the friction coefficient.

C. Obstacle Scenario

The basic idea of the obstacle scenario currently used is to make the patient’s movement visible, to provide a superior task, and consequently alteration in the training session. The way this is implemented is that the subject sees an avatar (figurine), whose movements are synchronized with his own movements. The avatar walks on a path with obstacles situated in a beach-inspired scenario. In Fig. 4, the technical setup for the obstacle scenario is shown. The resulting training scenario with multi-modal feedback and obstacles corresponds to the rehabilitation principle of repetition without repetition [21]. Gait as a repetitive movement is trained with obstacles challenging the patient to use a slightly different activation pattern. Thus, repetition without repetition can be achieved.

D. Frequency Response Measurement

In order to assess force and position bandwiths, a method for measuring the frequency response had to be established, based on related work [11]. One representative LOKOMAT drive unit was chosen (left knee drive). This drive unit contains the motor itself and sensors for rotation angle and force.

To measure angle and force frequency responses, two simple controllers were implemented. The controller used in the LOKOMAT contains an outer position feedback controller (proportional gain) and an inner force feedback controller (proportional gain).

All measurements were done without a human leg in the orthosis. The presence of a leg did not modify the results significantly in a series of test measurements.

1) Angle Frequency Response: The appropriate control scheme is shown in Fig. 5, a feedback proportional gain controller. The desired angle \( \varphi_{des} \) follows a sine signal and can be noted as \( \varphi_{des}(t) = \varphi_{des} \sin(2\pi ft) \). The amplitude for the desired angle \( \varphi_{des} \) was chosen to be 0.05 rad (about \( 3^\circ \)) to limit end-effector movement.

\[ \varphi_{des} \]

\[ P \]

\[ U_{drive} \]

\[ \varphi_m \]

\[ \text{Lokomat Drive Unit} \]

Fig. 5. Control scheme for measuring angle frequency response

2) Force Frequency Response: For force frequency response measurement, the left knee joint was blocked mechanically in a slightly flexed position. The force controller is displayed in Fig. 6. In addition to the proportional controller, a feed forward loop with gain \( P_F \) was implemented. The force amplitude \( F \) was chosen to be 10 N, with \( F_{des}(t) = F \sin(2\pi ft) \).

3) Excitation and Frequency Response Determination: Common for both angle and force frequency response mea-
measurement was the excitation principle. We sweep a constant-amplitude sine signal \( x(t) \), which can be noted as

\[
x(t) = \dot{x} \sin(2\pi f_i \cdot t) \quad \text{with} \quad f_i = \Delta f \cdot i,
\]

with \( i \) as sweep iterator, \( f_i \) as current sweep excitation frequency and \( \Delta f \) as excitation frequency increment. Each frequency \( f_i \) was applied in \( n \) repetitions.

The system response at each excitation frequency was determined with the Fourier transform. The \( i \)th frequency component of excitation signal \( x(t) \) and system response \( y(t) \) were computed. With \( X(\omega) \) denoting the Fourier transform of \( x(t) \) and \( Y(\omega) \) of \( y(t) \), we can find the complex frequency response \( G(f_i) \) with

\[
G(f_i) = \frac{Y(2\pi f_i)}{X(2\pi f_i)}.
\]

### E. Parameter Optimization

From the parameters that are used for haptic rendering (see section II-B), we concentrate on the penalty force with its parameters

- spring constant \( K \) and
damping coefficient \( B \).

Initial experiments showed that they had the most significant influence on the object contact phase. Stability problems mainly occurred in this stage of haptic interaction. An impulsive force with sine shape (duration: 100 ms) was used for all experiments.

Two experiments were carried out to assess both object hardness and contact phase stability for any spring constant

\[
K \in \{1000, 1500, 2000, 3000, 5000\} \text{ N/m}
\]

and any damping coefficient

\[
B \in \{50, 100, 200, 300, 500, 700\} \text{ Ns/m}^2.
\]

In a first experiment, the subject created short obstacle collisions (instruction: “Bounce back immediately!”) at three different approaching speeds (slow, medium, fast). Each approaching speed level was repeated five times, resulting in 15 collisions overall. The second experiment consisted of five longer obstacle collisions with slow approach (instruction: “Maintain contact for three seconds!”).

The first performance criterion object hardness can be computed using the concept of rate-hardness \( H_R \) with

\[
H_R = \frac{\text{initial force rate of change (N/s)}}{\text{initial penetration velocity (m/s)}}.
\]

This quality metric for hard virtual objects was found to correlate well with subject’s perception of object hardness [15]. Another metric to assess object hardness is maximum penetration depth. This makes only sense for limited and comparable approach velocities.

More difficult to assess is the contact phase stability during object contact. As stated earlier, the formal stability criterion of passivity is difficult to analyze with the nonlinear damping and impulsive force components used in the described approach. Therefore we will use a perception-based criterion here. It is clear that vibrations during the contact phase are detrimental for the perception of a solid object. Pretests showed that these vibrations occur within a frequency range of 3-8 Hz. Based on this observation a stability criterion can be derived by applying the Fourier transform to the hip and knee forces at every single object collision. The maximum in the designated frequency range then represents the amplitude of the most dominating vibration. An illustration of this method is shown in Fig. 7. One selected example for weak vibration (left side) and one for strong vibration (right side) are displayed. The Fourier transform was applied for the displayed section and divided by the section’s number of samples to eliminate the influence of longer contact duration in the strong vibration case. The vibration frequencies around 4 Hz and 8 Hz are clearly visible in the Fourier frequency spectrum. The maximum frequency amplitude is reflecting the different strength of oscillation and can be used as a contact phase stability criterion.

Another criterion for the same technical phenomenon is the time until the oscillation has faded. Therefore, the standard deviation of the right hip force and of the penetration depth within a running time window of width 200 ms were investigated. Oscillation time was defined from the beginning of object penetration till the standard deviation fell below a threshold (force threshold: \( s_F = 63 \text{ N} \), penetration depth threshold: \( s_p = 2 \text{ mm} \)). Force and penetration depth threshold were both used to determine the end of the oscillation time with the larger value being preferred.

### III. RESULTS

#### A. Frequency Response Measurements

The resulting Bode plots are shown in Fig. 8 and 9. It can be seen that the force frequency response diagram has a gap in the mid frequency range (50-100 rad/s, corresponding to 8-16 Hz). Measurements in this area caused heavy vibrations, thus they were abandoned. Angle bandwidth can be determined at 20 rad/s (3 Hz), force bandwidth at 50 rad/s (8 Hz) (considering only the stable area).

#### B. Parameter Optimization

The criterion rate hardness is a result of the first optimization experiment (multiple short object collisions). The resulting plot is shown in Fig. 10, left side. We see that in the lower left corner also low rate hardness prevails. The rate hardness increases with rising \( B \) and \( K \), interrupted by local peaks and gaps, which occur for \( K > 3000 \text{ N/m} \).
Obstacle hit for $K=1000$, $B=200$

Right hip force in N

Time in s

Obstacle hit for $K=5000$, $B=100$

Right hip force in N

Time in s

Fourier transform

FFT frequency amplitude

Frequency in Hz

Fig. 7. Illustration of contact phase stability criterion

Bode Diagram

Magnitude (dB)

Phase (deg)

Fig. 8. Bode diagram of angle frequency response
Maximal penetration depth was also analyzed from data of the first optimization experiment, results are displayed in Fig. 10, right side. The largest penetration depth is achieved for low $K$ values, while the opposite statement also holds (minimal penetration depth for high $K$). This observation is in accordance with the expected result. The damping coefficient $B$ has an influence as well, especially for $B \geq 300 \text{Ns/m}^2$ it increases the penetration depth, what is contradictory to expectations.

The second optimization experiment featured longer contacts with the virtual solid object. With regard to vibrations, Fig. 11, left side shows a relative mean for the occurrence and amplitude of vibrations. It can be seen that specific combinations of $K$ and $B$ ($K \geq 3000 \text{N/m}$) produce the largest vibrations. At $K = 5000 \text{N/m}$ and $B = 200 \text{Ns/m}^2$ a very low value exists.

A basically similar, yet different behaviour can be observed when analyzing oscillation time displayed in Fig. 11, right side. The general tendency (low $K$, low oscillation time) is similar to the previously discussed criterion. But in contrast, the influence of $B$ can be distinguished, a decrease in the oscillation time for increasing values of $B$.

IV. DISCUSSION AND CONCLUSION

The achieved force and angle bandwidths (8 Hz and 3 Hz, respectively) are very low compared to endeffector-based
haptic devices. This is because of the exoskeleton approach which results in high inertia. Other exoskeleton or gait-related devices show bandwidths in the same range or even lower. Therefore we can conclude that the LOKOMAT, although not constructed for high bandwidth, does still have the potential to be a haptic interface.

The results obtained for selected combinations of spring constant $K$ and damping coefficient $B$ reflect the conflicting demands of object hardness and contact phase stability. We can rule out the upper part of the optimization area ($K \geq 3000 \, N/m$) due to unwanted oscillations. The rate-hardness is unsatisfactory in the lower left corner ($K \leq 2000 \, N/m$, $B \leq 200 \, N_s/m^2$) and for all $K \leq 1500 \, N/m$. Maximal penetration depth gives similar constraints as rate-hardness. Thus we remain with a favorable combination of $K = 2000 \, N/m$ and $B = 300 \, N_s/m^2$. With this combination, the LOKOMAT can render a variety of solid objects (e.g. walls, obstacles, boxes, balls). However, due to the effects of high inertia and low force bandwidths the achievable hardness of solid objects is limited and the saturation of motor currents yields lower object hardness for higher approaching speeds. But for the intended use of creating immersive, interactive scenarios these drawbacks can be tolerated.

After all, the LOKOMAT, which was never constructed to be a haptic interaction device, can be used with some limitations for haptic rendering. Combined with other patient-cooperative strategies, haptic interaction — when implemented in combination with a virtual scenario — can be an important tool for therapists to make training sessions more challenging and motivating for patients, increasing therapeutic efficiency.

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