Assessment of walking performance in robot-assisted gait training: A novel approach based on empirical data

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Abstract

Motivation and voluntary drive of patients can be improved by applying biofeedback during robot-assisted rehabilitation trainings. Biofeedback systems were traditionally based on theoretical assumptions. In this paper, we present a novel approach to calculate biofeedback during robot-assisted gait training. Our method was based on empirical data that were obtained from healthy subjects when simulating distinctive degrees of walking performance during robot-assisted gait training. This empirical data-based biofeedback (EDBF) method was evaluated with 18 subjects without gait disorders. A higher correlation between the subjects' walking performance and biofeedback values was found for the EDBF method compared to a theory-based biofeedback approach.
Assessment of walking performance in robot-assisted gait training:
A novel approach based on empirical data

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I. INTRODUCTION

Patients with neurological movement disorders due to stroke or spinal cord injury were shown to benefit from task specific rehabilitation programs [1]. Robotic devices are becoming more and more established to enable or assist in task specific rehabilitation programs such as gait training [2-5]. These rehabilitation robots offer new possibilities to feedback performance related information to patients during their exercises [6], [7]. Such biofeedback might increase the training quality by fulfilling current motor learning principles.

The driven gait orthosis (DGO) Lokomat is one of the devices used to perform robot-assisted gait training with body weight support and a treadmill [3] and its efficacy was shown in different patient populations [8], [9]. The DGO was the first device with a reported biofeedback system for lower extremity robotic rehabilitation [7]. This pioneering “biofeedback” was based on theoretical biomechanical assumptions on patient-machine interaction forces measured at the hip and knee linear drives of the DGO. The validity of the biofeedback system was tested with a limited amount of subjects with and without neurological gait disorders [6].

A. The driven gait orthosis

The driven gait orthosis Lokomat is an exoskeletal structure that is used in combination with a body weight support system and a treadmill to conduct gait trainings with patients with neurological movement disorders. With the exoskeletal device, highly reproducible gait trajectories are repetitively generated. The DGO is equipped with sensors at the hip and knee linear drives to measure man-machine interaction forces.

Figure 1. The driven gait orthosis Lokomat is used in combination with a body weight support system and a treadmill. Force sensors are integrated in hip and knee linear drives.

B. Theory-based biofeedback calculation

The theory-based biofeedback calculation was described in detail elsewhere [6], [7]. The purpose of this biofeedback system was to differentiate active walking from passive behavior of the patients during training with the DGO. The biofeedback system was based on measured man-machine interaction forces in the hip and knee linear drives. These forces were processed in order to reward desired force production with positive biofeedback values, and passive behavior with negative values. In order to obtain these positive and negative values, forces were multiplied by weighting functions for the hip and knee joints for each gait
cycle and averaged for the stance and swing phase separately. With this procedure, eight biofeedback values were calculated for each step cycle: bilaterally for the hip and knee joint during stance and swing phase. Two theoretical assumptions formed the basis of this biofeedback system: 1) it was assumed that a good walking performance resulted in minimal (near zero) patient-machine interaction forces because the supporting or resisting force applied by the DGO would be minimal when a subject was able to match the movement of the exoskeleton. 2) The amplitudes of the weighting functions were mainly based on joint angular velocity, i.e. the gait sections with the highest joint angular velocity received the highest weight. In addition, the weighting function of the knee was set constant for the stance phase because knee extension is required during the whole period. A cosine-function was introduced during the swing phase of the hip, where forces are partly resulting from gravity (Fig. 4).

With only four force sensors, the amount of available information to generate biofeedback is very limited. In addition, the interaction forces are not only influenced by the walking performance of the patient, but by other factors such as the amount of body weight support, body positioning within the exoskeleton, treadmill speed and the synchronization between the movements of the exoskeleton and the speed of the treadmill. The influence of these factors is often not known and difficult to predict or control. Therefore, instead of building a complex biomechanical model with numerous unknowns and assumptions, we developed a biofeedback system that was based on empirical data obtained in controlled measurements.

II. EMPIRICAL DATA-BASED APPROACH

A. Empirical data collection

Data of two subjects without neurological gait disorders were extracted from a database that was established to describe man-machine interaction forces in robot-assisted gait training (paper submitted for publication [10]).

For the measurements, the subjects were mounted to the DGO according to the guidelines of the manufacturer. The treadmill speed was set to 0.7m/s with the lowest possible amount of body weight support for which knee buckling was still prevented with passively behaving subjects. The synchronization between the treadmill and the movements of the exoskeleton was set automatically by an iterative learning algorithm [11]. Two measurements were conducted with the following instructions: 1) Subjects participated actively in the walking movements by matching their walking movements with the trajectories of the exoskeleton. 2) The subjects simulated a flaccid patient by behaving passively and not contributing to the stepping movements. During the measurements of 30 seconds duration, forces in the hip and knee linear drives were recorded bilaterally together with hip and knee joint angles and a heel strike trigger signal with a sampling rate of 100Hz.

B. Reference man-machine interactions

For each subject, the force signal was cut into single step cycles and normalized to 1000 data points per step cycle. Average interaction force curves were calculated for the active and passive state of the two subjects. This procedure resulted in one “active”, and one “passive” interaction force reference curve (Fig. 3).

C. Calculation of biofeedback values

Biofeedback is calculated for the hip and knee during stance and swing phase according to the following equation:

\[ FB_{j,p} = a \left( \int_{a_{j,p}} s(a) \right) + z_{j,p} \]

where \( FB \) is the biofeedback value, \( j \) is the joint with \( j = 1 \) for hip and \( j = 2 \) for knee, \( p \) is the gait phase with \( p = 1 \) for stance and \( p = 2 \) for swing, \( a \) is a subsection of the gait cycle, \( fb \) is the biofeedback value for a subsection of the gait cycle, \( s \) is a factor to assign a positive or negative sign to the biofeedback value and \( z \) is a constant to compensate the offset for the passive components of the DGO.

The biofeedback values of the different subsections of the gait cycle \( fb(a) \) are calculated according to the following equation:

\[ fb_{a_{j,p}} = \int_{[k]} \left( c_{j,p}[k] \cdot \left( y_{j,k} - y_{j,active}[k] \right) \right) \]

where \( c \) is a weighting function and \( k \) is the time point during the gait cycle with \( k = \{1, 500\} \) for the stance phase
and \( k = \{550, 1000\} \) for the swing phase, \( y \) is the measured man-machine interaction force and \( r^{\text{active}} \) is the active reference force curve. The difference between the measured interaction force curve \( y[k] \) and the reference interaction force curve \( r[k] \) is calculated for each time point during the step cycle \( k \) in order to determine the deviation of the measured interaction force curve of a subject from the “ideal” walking performance. The difference \( y[k] - r^{\text{active}}[k] \) is multiplied by a corresponding weighting function \( c[k] \).

Stance and swing phase are divided into subsections \( a \) in order to judge the biofeedback values, i.e. to assign positive biofeedback values for desired and negative biofeedback values for unsatisfactory walking performance. Four cases are differentiated, where the sections \( a \) are determined by the constellation of the algebraic signs of the functions \( c[a] \) and \( r^{\text{active}}[a] \):

\[
\begin{align*}
 r^{\text{active}}[a] & \leq 0 \\
 c[a] & \leq 0 \\
 \implies y[a] & \geq r^{\text{active}}[a] \to \text{positive fb}_a
\end{align*}
\]

(3.1)

\[
\begin{align*}
 r^{\text{active}}[a] & \leq 0 \\
 c[a] & > 0 \\
 \implies y[a] & \geq r^{\text{active}}[a] \to \text{positive fb}_a
\end{align*}
\]

(3.2)

\[
\begin{align*}
 r^{\text{active}}[a] & > 0 \\
 c[a] & \leq 0 \\
 \implies y[a] & \leq r^{\text{active}}[a] \to \text{positive fb}_a
\end{align*}
\]

(3.3)

\[
\begin{align*}
 r^{\text{active}}[a] & > 0 \\
 c[a] & > 0 \\
 \implies y[a] & \geq r^{\text{active}}[a] \to \text{positive fb}_a
\end{align*}
\]

(3.4)

The factor \( s(a) \) in equation (1) is \( s(a) = 1 \) in case of the constellations described in (3.2) and (3.4) and \( s(a) = -1 \) in case of the constellations described in (3.1) and (3.3). This procedure assures that desired walking performance results in \( \text{fb}_a \cdot s(a) \geq 0 \) which corresponds to a positive biofeedback value.

D. Weighting functions

\[
c_{j,p}[k] = \frac{r^{\text{active}}[k] - r^{\text{passive}}[k]}{\max\{r^{\text{active}}[k], r^{\text{passive}}[k] \}}
\]

(4)

The weighting functions were constructed by calculating the difference between the “active” interaction force reference curve \( r^{\text{active}}[k] \) and the “passive” interaction force reference curve \( r^{\text{passive}}[k] \) at any time during the gait cycle. The normalization with the divisor was conducted separately for the stance phase with \( k' = \{1,500\} \) and swing phase with \( k' = \{550,1000\} \) of the hip \( (j=1) \) and knee joint \( (j=2) \). With this procedure, the observed force difference determined the amplitude of the weighting function for each time point within the gait cycle, i.e. the sections with the highest observed interaction force differences were weighted the highest.

III. EVALUATION OF THE EMPIRICAL DATA-BASED BIOFEEDBACK

The empirical data-based biofeedback method (EDBF) was evaluated and compared to a theory-based biofeedback approach by applying both methods to a preexisting data set of man-machine interaction forces (paper submitted for publication [10]). These data were measured in 18 (10 female) healthy subjects without neurological gait disorders. The study protocol was approved by the local Ethics committee and conformed to the Declaration of Helsinki. All subjects gave written informed consent before inclusion in the study. The subjects had an average weight of 69.7 (standard deviation = 10.9) kg, a height of 172.9 (9.1) cm and were 26.2 (3) years old. Measurements of man-machine interaction forces were conducted as described above for the reference subjects. During the measurements, patients were blinded from their produced biofeedback values. The reference subjects did not participate in the evaluation measurements.

Biofeedback values were calculated offline by the presented EDBF method and by the theory-based biofeedback method for each step of the “active” and “passive” conditions of every subject, resulting in approximately 15 biofeedback values for each joint during stance and swing phase in each condition. For each subject, it was analyzed whether an increase in walking performance (from “passive” to “active”) resulted in an increase (positive correlation), a decrease (negative correlation) or no statistical difference of the corresponding biofeedback values. (Wilcoxon signed rank test with \( \alpha < 0.05 \)). These results were summarized for all subjects and percentages of positive, negative or no correlations were determined for each joint during stance and swing phase (Table 1).

IV. RESULTS

With the EDBF, an increase in walking performance resulted in a significant increase of knee biofeedback values during stance phase in 100% of the cases, compared to 17% with the theory-based biofeedback method (TBF). For the swing phase of the knee, a positive correlation between walking performance and biofeedback values was found in 63% of the cases with the EDBF method and in 64% of the
cases with the TBF. For the hip, a positive correlation between walking performance and feedback values was found in 92% of the cases for the stance phase and in 75% of the cases for the swing phase with both methods. For the stance phase of the hip and knee, less negative correlations were found with the EDBF method, i.e., there were less false interpretations of the walking performance.

### Table 1

<table>
<thead>
<tr>
<th></th>
<th>Positive (observed cases in %)</th>
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<tbody>
<tr>
<td></td>
<td>Correlation</td>
</tr>
<tr>
<td></td>
<td>TBF</td>
</tr>
<tr>
<td>Hip stance</td>
<td>92</td>
</tr>
<tr>
<td>Hip swing</td>
<td>75</td>
</tr>
<tr>
<td>Knee stance</td>
<td>75</td>
</tr>
<tr>
<td>Knee swing</td>
<td>63</td>
</tr>
<tr>
<td>TBF</td>
<td>92</td>
</tr>
<tr>
<td>EDBF</td>
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</tr>
<tr>
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<td>11</td>
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The validity of the theory-based (TBF) and the empirical data-based biofeedback (EDBF) is described by the number of observed cases with a positive or negative correlation between the walking performance of the subject and corresponding biofeedback values.

### V. Conclusion

In conclusion, we presented an empirical data-based biofeedback method for robot-assisted gait training applied to the DGO Lokomat. However, this method could be applied to all robotic rehabilitation devices equipped with position and force sensors, where patients move their limbs along a desired trajectory. With this approach, biomechanical models with many assumptions and unknowns can be avoided. Only a small number of subjects is needed to obtain the reference data which are necessary for this simple, yet effective biofeedback strategy.

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### References


