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Locomotor adaptation and retention to gradual and sudden dynamic perturbations

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Abstract—**Motor learning principles are increasingly used in robotic rehabilitation. These principles are mainly derived from reaching studies and it is currently unknown whether the same principles apply in locomotion. The aim of this study was to determine the effect of a gradually and suddenly introduced dynamic perturbation on locomotor adaptation and on recalling the adaptation when being re-exposed to the same perturbation. Subjects walked on a treadmill and adapted to a viscous force field that was applied during the swing phase. In one group the strength of the force field was gradually increased over different steps whereas in a second group it was introduced suddenly at full strength. The gradual group showed less adaptation and a faster decay of the adaptation during the washout than the sudden group. Strikingly, when both groups were being re-exposed to the perturbation at full strength, the gradual group showed no adaptation whereas the sudden group showed a faster occurring adaptation than during the first exposure. In conclusion, in contrast to the reported beneficial effects of a gradual introduction of a perturbation on adaptation in reaching, it seems to have a detrimental effect on locomotor adaptation. These results indicate that caution should be taken when applying motor learning principles solely derived from reaching studies to improve robotic gait rehabilitation.**

Keywords: motor adaptation, force fields, gait, rehabilitation robots, retention.

I. INTRODUCTION

Neurorehabilitation can be considered as a process to relearn task directed movements. More and more, concepts from motor learning are adopted in rehabilitative training programs and schedules to further improve the functional outcome. This is especially true for robotic rehabilitation. For instance, knowledge about how humans learn/adapt is incorporated in control algorithms of robotic devices to automatically adapt the amount of support to the patient's needs and encourage the patients to actively participate in the training [1]. Further insights into motor adaptation and how it can be facilitated could further improve the interaction between the robot and human and the training schedules to promote relearning.

In recent years, different factors have been identified that can improve the amount of adaptation and/or the retention. The amplification of execution errors during learning enhances the amount of adaptation [2] and more time between the different trials during training improved retention [3]. Furthermore, different studies have shown that a gradual introduction of a perturbation, which prevents subjects from experiencing large movement errors, facilitates motor adaptation in reaching. Adaptation was found to be more complete [4, 5]. Additionally, short-term [6] and long-term retention was better [5] than when the perturbation was introduced suddenly.

Most motor learning principles have been derived from studies investigating arm-reaching movements. Relatively few studies have been performed to investigate motor learning during locomotion [7-13]. It is questionable and largely unknown whether the principles that were found in reaching studies also apply to locomotor adaptation. Some studies have provided evidence that the basic adaptation mechanisms are the same. Lam and colleagues [14] showed that subjects adapt to a viscous resistance applied at the hip and knee by updating an internal model of the limb dynamics that is used to calculate the motor commands for a specific movement. This was in accordance with the observed adaptation in response to viscous force field applied during reaching [15]. How the internal model is updated is reflected in the evolution of the execution errors during learning. Emken and colleagues [10] showed that subjects updated their internal model in response to a viscous force field applied at the ankle based on the experienced error and the strength of the force field in the previous step. This error-based learning rule was previously shown to hold for reaching [16, 17]. Though the basic underlying mechanisms might be the same, we still need to assess whether the previously identified factors that facilitated motor adaption in reaching also promote locomotor adaptation.

The aim of this study was to determine the effect of a gradually and suddenly introduced dynamic perturbation on locomotor adaptation, and on recalling the adaptation when being re-exposed to the same perturbation. We hypothesized that a gradual introduction of the force field would result in a more complete adaptation and a better recall during re-exposure.

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II. METHODS

A. Subjects

Seventeen healthy subjects (10 males and 7 females, age: 25.0 ± 4.4 years, height: 1.79 ± 0.07 m, weight: 74.3 ± 11.5 kg) were recruited to participate in this experiment. All subjects gave written informed consent to participate in this study.

B. Experimental apparatus and recordings

Subjects' legs were attached to the robotic gait training device LOPES by using leg cuffs around the mid-thigh, upper shank and lower shank. LOPES is an impedance controlled device with 8 actuated degrees of freedom (flexion/extension at the hip and knee, abduction/adduction for both legs and horizontal pelvis translations). An extensive description can be found in Veneman et al [18]. The degrees of freedom and the applied control allow unhindered walking in healthy subjects [19]. The lengths of the LOPES linkages and the width of the pelvis were adjusted to each individual subject to assure proper alignment of the LOPES exoskeleton joint axes and the human joint axes. As the exoskeleton did not encompass an ankle joint, the ankle and foot were left free to move. The integrated position sensors at the exoskeleton joint axes were used to record the movements of the subjects during the experiment.

The robotic device was used to apply a viscous force field during the swing phase of the left leg. The robot was controlled to apply a virtual vertical downward force at the ankle that was proportional to the ankle's forward horizontal velocity ($\dot{x}_{ank}$).

$$F_y = \begin{cases} -B\dot{x}_{ank}, & \dot{x}_{ank} > 0 \\ 0, & \dot{x}_{ank} < 0 \end{cases} \qquad (1)$$

where F_y is the vertical force and B is the strength of the viscous damping. The strength of the force field varied between experimental groups. The ankle's forward velocity was obtained by differentiating the ankle position, which was derived from the recorded joint angles and the subject's segment lengths using forward kinematics.

As LOPES does not control forces directly at the ankle, this virtual force was mapped to the corresponding torques at the hip (τ_{hip}) and knee (τ_{knee}) by using a Jacobian (J^T)

$$\begin{bmatrix} \tau_{hip} \\ \tau_{knee} \end{bmatrix} = J^T \begin{bmatrix} F_x \\ F_y \end{bmatrix} \qquad (2)$$

C. Experimental protocol

Subjects were randomly assigned to two groups, a sudden group (SUD) and a gradual group (GRAD). All subjects walked on a treadmill at a speed of 3 km/h. Before the actual experiment started, subjects walked 3-4 minutes with the robot in zero-force (transparent) mode to familiarize themselves with walking in LOPES. The experiment consisted of one walking trial in which periods of exposure to the force field were alternated with periods of no perturbation. The trials began with a baseline phase (BAS) in which subjects walked 40 strides without any perturbation (B=0). Subsequently subjects were exposed for the first time to the perturbation (EXP1) for 80 strides. For the sudden group, the force field was turned on with full strength (B=30 Ns/m), whereas for the gradual group, the strength of the force field was gradually increased from 0 to 30 Ns/m over the first 60 steps. Subjects then again walked in the absence of the force field for 120 strides. This phase was the first "washout" phase (WASH1). Following, subjects were re-exposed to the perturbation for 80 strides (EXP2) and had another washout phase for 120 strides (WASH2). During re-exposure the force field was introduced at full strength for both groups of subjects. The variation of force field strength with the stride number is depicted in Fig 3B for both groups. Prior to the trial, subjects were instructed to walk as normal and consistently as possible and they were not warned or informed about the application or removal of the force field.

D. Data analysis.

To quantify the adaptation process we calculated the ankle height during mid swing, defined as the moment at which the horizontal ankle position passes the horizontal hip position. The baseline performance was determined by averaging the parameters over the last 5 steps of the BAS phase. The changes in the parameters were grouped and averaged in bins of 5 movements and expressed relative to this baseline.

E. Statistical analysis.

All statistical tests were performed by using SPSS (IBM SPSS, Somer, NY) and for all tests the significance level was set at an alpha value of 0.05. Student's t-test (paired and independent) and repeated measures ANOVA were used in the between groups and within group comparisons.

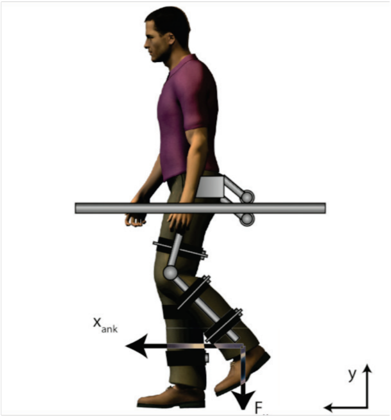

Fig 1. Schematic overview of the LOPES robotic device. The device exerts knee and hip torques on the human limb, which corresponds to a downward force at the ankle.

III. RESULTS

The SUD group responded different to the first exposure of the force field than the GRAD group (see Fig 2). The introduction of the force field resulted in a downward shift of the ankle height patterns. For the GRAD group these initial effects were less clear as the force field was still very weak during these first steps. At the end of the first exposure, the SUD subjects were effective in compensating for the force field as the ankle height patterns were on top of those during the baseline phase. In contrast, the GRAD group still showed ankle height patterns

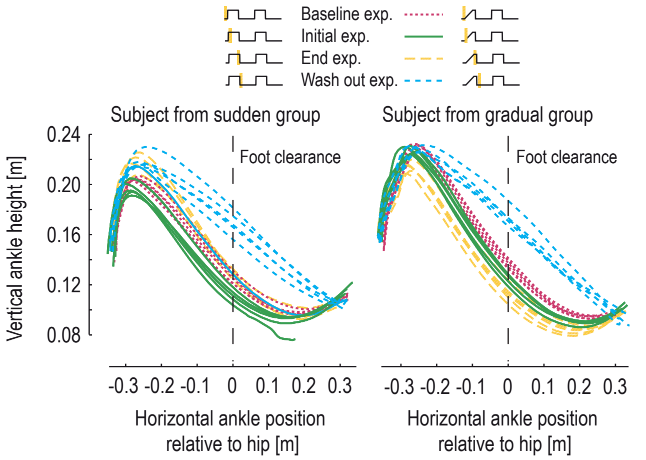

Fig 2. Paths of the ankle from two selected subjects. The paths are shown for different portions of the first exposure to the force field. Yellow boxes in the legends show the range of steps shown. For each of the portions five consecutive steps are shown.

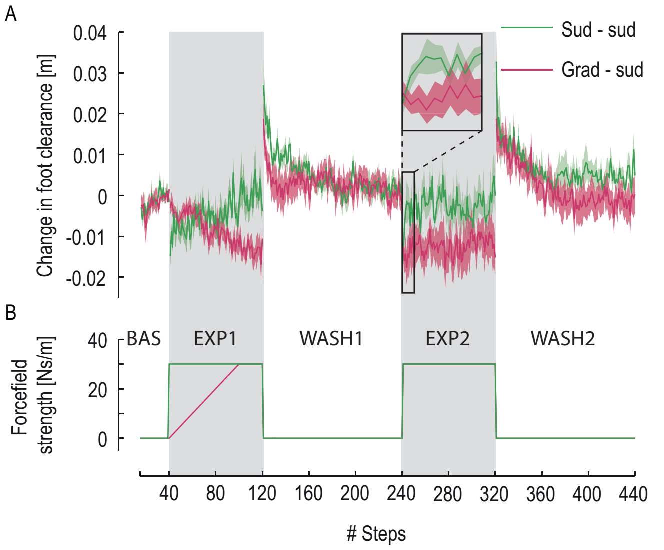

Fig 3. Adaptation of the foot clearance (A) to exposure and re-exposure of the force field. Curves show the mean across subjects as a function of the step number for the different groups. The height of the shaded area represents ± SE. Values are expressed as changes relative to the baseline value which is determined from the five steps preceding the first exposure. (B) strength of the force field as a function of the step number.

that were well below those observed during baseline. Still also the GRAD group did adapt to compensate for the perturbation as was evident from the clear after effects (increased ankle height) during the first steps of the washout phase.

Examination of the step-by-step changes for the foot clearance (see Fig 3 and 4) showed that the GRAD group adapted less than the SUD group as expressed in a significantly lower foot clearance in the last movement bin of EXP1 [t-test, t(15)=-3.23, p<0.05]. The increase in foot clearance at the beginning of WASH1 was not significantly different between both groups (independent t-test, t(15)=-1.947, p=0.07). Yet, the after effect decayed significantly faster in the GRAD group. This was evident from a significant group x movement bin interaction effect [2 way (group, movement bin) repeated measures ANOVA, F(2,30)=6.463, p<0.05]. In addition, we fitted a single-exponential function on the average curves during WASH1 for both groups. The GRAD group foot clearance declined with a time constant of $\tau=2.9$ (so after 2.9 movements 63 % of the after effect was decayed) whereas the time constant for the SUD group was $\tau=20$.

Both groups were re-exposed to the force field after WASH1 to investigate whether the characteristics of the first exposure block influenced retention during re-exposure. Now the force field was introduced suddenly for both groups. Both groups returned to baseline levels before re-exposure and the foot clearance at the end of WASH1 (just before re-exposure) did not differ significantly between groups (independent t-test, t(15)=-0.062, p=0.951). The initial change in foot clearance during EXP2 did also not differ significantly between both groups (independent t-test, t(15)=-1.965, p=0.068). Furthermore the initial change for the SUD group during EXP2 did not significantly differ from the initial change during EXP1 (paired t-test, t(7)=-1.460, p=0.188). Yet, the amount of adaptation during re-exposure differs between the groups. The GRAD group does not show evidence of adaptation as the foot clearance at the end of EXP2 was not significantly different from the start of EXP2 (paired t-test, t(8)=-0.574, p=0.582). Furthermore, there was a very strong trend that the foot clearance a the end of EXP2 was smaller for GRAD than for SUD (independent t-test, t(15)=-2.127, p=0.05). The SUD group showed evidence for savings. During re-exposure, subject reached an asymptote in adaptation in about 3 movements; this asymptote was at the same level as the end level during first exposure. During the first exposure subjects did not yet reach an asymptote after 80 movements.

Remarkably, despite the clear differences in adaptation during EXP2, both groups showed similar washout effects in magnitude (independent t-test, t(15)=-0.870, p=0.398) and in the course (No group x movement bin interaction effect in repeated measures ANOVA, F(2,30)=0,271, p=0.764].

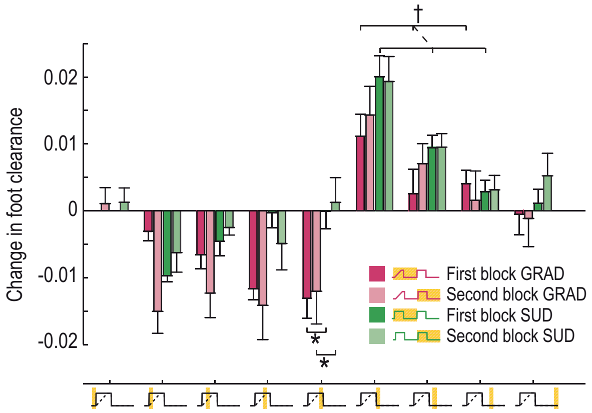

Fig 4. Comparison of the average changes in foot clearance for the first and second block of exposure and wash out. Each bar represents values obtained by averaging over 5 steps at specific portions of the block and subsequently averaging across subjects. Error bars indicate SE, * indicates a significant difference between the groups and † indicates a significant interaction effect between group and portion of wash out phase.

IV. DISCUSSION

The purpose of this study was to determine the effect of gradually and suddenly introduced dynamic perturbations on locomotor adaptation. A gradual introduction of the perturbation does not seem to have the same beneficial effects on locomotor adaptation than it has on adaptation in reaching. Adaptation in response to a gradual perturbation produced less adaptation and adaptation that decayed faster than adaptation in response to a sudden perturbation. Furthermore, the adaptation to the gradual perturbation seems to inhibit the adaptation process when being re-exposed to the same perturbation. However, the results during the washout period of this re-exposure seem to contradict this observation, as the washout showed clear after effects.

The "inhibitory" effect of the previously experienced, gradually introduced force field has not been demonstrated before. So far only positive effects of a gradual introduction have been reported. Recently, Huang & Shadmehr [6] demonstrated that prior experience in a gradual changing force field resulted in lower decay rates after being re-exposed to the same force field than when subjects were initially exposed to sudden change. There are two possible explanations for our findings. First, it could be that during walking people provide more priority to a safe walking pattern than to restoration of normal kinematics that is reducing motor errors. A gradually changing force field let subjects slowly accustom to the force field and experience that there is no real need to adapt. They can still walk safely even when the force field is at its full strength. When being re-exposed, the subjects recognize the perturbation and remember that there is no need to adapt. On the contrary, a sudden introduction of the force field during the first exposure will be regarded more as a threat for safe walking and therefore subjects adapt. During re-exposure, subjects remember the perturbation and recall the strategy to counter act the perturbation, which results in a faster learning rate. Second, the subjects who first experience the gradually introduced force field might have adopted a different adaptation strategy, which was not captured by the parameter we chose to quantify adaptation. Changes in hip and knee angles are reflected in our parameter (changes in ankle height) but changes in ankle angles are not. Possibly, they adapted by increasing the dorsiflexion during swing. To be able to distinguish between these explanations we need to quantify changes in the ankle angle during the adaptation process.

One finding of our study clearly deviates from other experimental findings in locomotor adaptation. As mentioned above, we observed that the sudden group showed evidence for savings in that they adapted faster during re-exposure. Emken and colleagues showed that repeated exposure [10, 20] , even up to 10 times, did not result in faster learning rates or smaller initial errors upon re-exposure. This difference cannot be explained from the number of steps between the different exposures, as they used only 25 steps between exposures while we used 140 steps. A possible explanation could be that they used a force field that provided an upward force at the ankle, effectively increasing the step height, whereas in our study a downward force was provided. As this downward force has a larger destabilizing nature, there is a larger need to remember this force field.

The adaptation results for the re-exposure of the gradual group seem to show a contradiction. The results during adaptation suggest that there was no adaptation whereas the results during washout suggest that there was adaptation. One possible explanation could be that the chosen parameter to quantify the adaptation process was not appropriate. We used the foot clearance at mid swing, as at this moment the amount of foot clearance is most critical. However it could be that the central nervous system is controlling the foot clearance at a different point. Therefore we also quantified the adaptation process using the area below the footpaths (as depicted in Fig. 2), as this captures the complete foot trajectory during swing. These results showed exactly the same pattern. Another explanation could lie in a complex interaction between feedback and feedforward control during the adaptation process. Possibly, at the start of re-exposure reflex activity assured that the foot clearance did not get too low and so prevented subjects from stumbling. During the course of re-exposure the feedback control was "substituted" by feedforward control without further improving the performance. Yet, during the washout this contribution of feedforward would become apparent. Previous studies have shown that the response to dynamic perturbations during walking is a mix of feedforward and feedback responses [12, 14]. Only by measuring the muscle activity during the adaptation process we will be able to assess the validity of this explanation.

In conclusion, the basic principles in reaching adaptation do not all hold in locomotor adaptation. This implies that caution should be taken in implementing these principles in robotic gait rehabilitation.

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