Influence of reaching direction on visuomotor adaptation: an explorative study

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Abstract—Robotics is increasingly used in rehabilitation therapy of the hemiparetic arm after stroke. Several studies performed adaptation experiments to gain more insight in the underlying learning processes. In these studies adaptation during reaching movements in different directions is assessed. No information about influence of direction on the amount of learning to these separate directions is present. In this paper we assessed the effect of reaching direction on visuomotor learning. Forty healthy subjects performed 48 movements to five different directions during adaptation to a 30 degrees visuomotor rotation. The execution error was defined as the initial direction error at peak velocity and after 100 ms after onset of the movement. The amount of learning was defined as the difference between the start value and the end value of the execution error. A significant higher amount of adaptation in the movement towards the contralateral part of the body (-72) compared to reaching towards other directions was observed. When possible feedback and corrections mechanisms are taken into account; results indicate that subjects adapt most towards -72 direction and least towards -144 direction. Data of healthy elderly and stroke survivors would be essential to test whether observed results are present in these populations as well, which could have implications for motor relearning in rehabilitation therapy.

Keywords: adaptation, cva, direction, learning, reaching, rehabilitation, stroke, visuomotor

I. INTRODUCTION

Robotics is increasingly used in rehabilitation therapy of the hemiparetic arm after stroke. From several studies it is known that robot aided therapy can contribute to enhanced motor learning in stroke survivors. [1, 2] Robotics can also be used to gain more insight into underlying learning processes by means of visuomotor adaptation experiments. It is known that stroke survivors have the ability to adapt to changing environments, which is the basis for their ability to learn. [3] Insight from adaptation experiments of healthy subjects [4, 5] could also contribute to a better understanding of motor learning in stroke survivors. These studies could demonstrate the potential use of robotic error-enhanced therapy for motor learning in rehabilitation settings for stroke survivors.

Visuomotor adaptation experiments use a perturbed spatial relationship between vision and action to study motor (re)learning. This can be achieved by altering the visually perceived location of a target in such a way that it appears to be at a point in space different from its actual location. This results in a discrepancy between the observed and perceived location of a target. When subjects reach toward a target without being able to see their hand, they will initially reach toward the visual location of the target and will not be able to reach the target. Due to the provided error-feedback subjects are able to learn to anticipate to the applied misalignment, after repetitive movements, this can result in a decreased error. [6]

Generally in these experiments reaching movements are made in different directions. Data from different movement directions is gathered to constitute a learning curve. [3, 7] Earlier research has been performed into the amount of trials necessary to learn to one or more directions. [8] They found slower total rate of learning of the applied rotation with multiple directions, compared to one direction. But the rate of adaptation was equal for the different directions when plotted as a function of the number of repetitions to the specific direction. This would indicate that a similar adaptation occurs to each direction independently and there is no difference between adaptation rates into different directions. However, recent results from our pilot study gave indications that differences in amount of motor adaptations might exist between different directions. Therefore, in this explorative study we further explore the influence of movement direction on visuomotor adaptation in healthy subjects.

II. METHODS

A. Subjects

Forty healthy subjects between the ages of 18 and 26 were included in the experiment. They all had normal or to normal corrected vision, were right handed and had no motor or cognitive impairments. All subjects gave their written informed consent prior to the experiment.
B. Set-up and apparatus

Subjects were seated and made reaching movements in the horizontal plane with their right arm holding the end effector of a 3D haptic robot, the HapticMaster (Moog FCS, Nieuw-Vennep, the Netherlands). The arm robot was placed in a closet-like box. The combination of a mirror and projection screen gave the illusion that the projected image was in the same horizontal plane as the hand. The subjects were instructed to look into the mirror to see a projection of their right-hand position on a screen located parallel and just above the mirror. The mirror also prevented direct sight of the arm. The arm was supported against gravity by a support mechanism that allowed low-friction movements over the underlying surface; see figure 1. The visual scene was updated with a frequency of 100 Hz.

C. Reaching task and procedure

Subjects performed centre-out reaching movements with their right hand to one of five different targets equally spaced (72 degrees apart) about the perimeter of a circle of 10 cm radius (figure 2). The hand position was indicated with an 8 mm blue sphere, in the following referred to as “cursor”. The targets were presented as yellow spheres with a 17 mm diameter.

The starting posture was obtained by a shoulder plane of elevation of 45 degrees, shoulder elevation angle of 90 degrees, and elbow flexion of 90 degrees [7]. At the start of each trial, a target was presented and a short beep triggered the initiation of the movement. A cycle consisted of one trial to each direction (five movements). The order of the directions was randomized per cycle to prevent sequence learning. Between movements, the cursor was made invisible while the arm was returned to the initial position by the robot.

D. Data analysis

Movement position of the hand was used to assess the execution error of the subjects during the learning phase. The direction error at peak velocity was used as a measure of the execution error. The direction error was defined as the angle between the vector from the starting point to the cursor position at maximum velocity and the vector from the starting position to the target. A positive value meant that the movement path was on the counterclockwise side of the ideal path, and a negative value meant a movement path on the clockwise side of the ideal path.

A total of 48 repeated movements to all five targets is obtained. From this, five learning curves of all the different targets can be plotted. The amount of learning is calculated as the difference between the start (first sample) and end (last sample) value of the execution error per subject and per direction. This results in a positive value if the end execution error is lower than the start execution error. This was calculated for all forty subjects per direction, for all five directions.

The movement speed was varied over the subjects. No interaction effects were observed over the movement directions. But to exclude possible effects of perceived feedback and movement corrections due to the different movement speeds, we also performed analysis at 100 ms after onset of the movement. Subjects will not have been able to generate any feedback corrections in the first 100 ms after movement onset.
E. Statistics

The amount of learning is compared between the five different movement directions using a five levels (different directions) repeated measures ANOVA. If any differences were found, post hoc comparisons were made and Sidak adjustments were used to correct for multiple tests. If missing values were present for one of the directions, data of that subject could not be used in the statistical analysis.

III. RESULTS

A. Direction error at maximum velocity

In figure 3 the averaged learning curves plus and minus their standard deviation are shown for the different directions. From the learning curves it can be observed that direction -72 seems to have a larger execution error at the start and a smaller execution error at the end of the learning phase, compared to the other four directions. Per direction the execution errors at the start of the movement (the first sample) and at the end of the movement (last sample) were averaged over the subjects (table 1).

These observations were supported by a statistical repeated measures ANOVA analysis. Near significant different start values were observed between -72 and 0 direction (p=0.059), and -72 and 144 direction (p=0.052). A significant different end value was observed between -144 and -72 direction (p=0.00), between -144 and 0 degrees direction (p = 0.005), and -14 and 72 direction (p=0.043).

<table>
<thead>
<tr>
<th>Direction</th>
<th>Execution error ± standard deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Start (n=40)</td>
</tr>
<tr>
<td>-144</td>
<td>25.07±13.88</td>
</tr>
<tr>
<td>-72</td>
<td>30.54±15.37</td>
</tr>
<tr>
<td>0</td>
<td>22.13±11.01</td>
</tr>
<tr>
<td>72</td>
<td>23.42±11.72</td>
</tr>
<tr>
<td>144</td>
<td>20.55±13.12</td>
</tr>
</tbody>
</table>

![Figure 3](image-url) The learning curves of the execution error for the five directions. The lines represent averages across all subjects, plus and minus the standard deviation.
A significant difference in amount of learning between the different directions was found \((p < 0.05)\). Post hoc analysis revealed significantly larger amount of learning towards the -72 direction, compared to three other targets (-144, 0, 144), respectively, \(p = 0.007, p = 0.014, p = 0.041\). A near significant effect was observed between -72 and 72 direction \((p = 0.064)\). No other statistical significant differences were revealed by this analysis.

**B. Direction error after 100 ms**

From the start and end values and the amount of learning it can be observed that direction -72 seems to have a larger execution error at the start and a smaller execution error at the end of the learning phase, compared to the other four directions. Per direction the execution errors at the start of the movement (the first sample) and at the end of the movement (last sample) were averaged over the subjects (table 2).

These observations were supported by a statistical repeated measures ANOVA analysis. A significant different end value was observed between -144 and -72 direction \((p=0.004)\), and between -144 and 0 degrees direction \((p=0.021)\). No further statistical significant differences were revealed (amount of learning \(p>0.65\), start value \(p>0.87\)).

**TABLE II.** The execution error after 100 ms averaged over all subjects, per direction, at start and end of the learning phase, and the average amount of learning \(\pm\) standard deviation.

<table>
<thead>
<tr>
<th>Direction</th>
<th>Execution error (\pm) standard deviation</th>
<th>Average amount of learning (\pm) standard deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>-144</td>
<td>30.68(\pm)21.52, 11.37(\pm)9.74</td>
<td>19.43(\pm)23.69</td>
</tr>
<tr>
<td>-72</td>
<td>33.89(\pm)25.02, 2.33(\pm)13.62</td>
<td>31.87(\pm)31.38</td>
</tr>
<tr>
<td>0</td>
<td>28.82(\pm)25.32, 5.89(\pm)8.91</td>
<td>22.65(\pm)25.02</td>
</tr>
<tr>
<td>72</td>
<td>36.60(\pm)23.14, 5.82(\pm)10.15</td>
<td>29.07(\pm)20.21</td>
</tr>
<tr>
<td>144</td>
<td>30.75(\pm)17.02, 9.85(\pm)16.87</td>
<td>23.70(\pm)20.76</td>
</tr>
</tbody>
</table>

We also tested whether the observed higher initial value towards the -72 direction was due to the order of movement directions. No order effect between the directions was found.

**IV. DISCUSSION**

In this study we explored the influence of movement direction on amount of visuomotor adaptation in healthy subjects. Analysis at peak velocity show larger adaptation to -72 direction compared to other directions. When possible feedback and corrections mechanisms are taken into account; results indicate that subjects adapt most towards -72 direction, and least towards -144 direction.

The difference in observed directional errors at peak velocity and after 100 ms of the onset of the movement can be related to feedback and corrections mechanisms. The movement time from onset till peak velocity is typically around half of the movement (\(\approx\)250 ms)[8]. Therefore subjects had more time, compared to the directional error at 100 ms, to execute corrections for the calculated directional error at peak velocity. Observed differences in the end values of -144 and -72 directions are also present after 100 ms. This could indicate that, in line with a study of Krakauer et al [9] who found that different adaptation rates are present for different directions, updating of the internal model occurs in different ways for different directions, independent of the amount of feedback available. It is of interest to notice that main results are observed in the directions across the midline.

The observed differences of adaptation into different directions may also be related to the contribution of multi- or single joint movements. From literature it is suggested that movements across the body usually have a more curved path and are accounted for by more single joint movements.[10] During the performed task in the present study, both multi- and single -joint movements were necessary to execute movement towards the different directions. Although no kinematic data from joint angles was available, it could be there is a different use of elbow and shoulder muscles for the different directions. [11-13] This information would be of interest for understanding motor learning and movement control in neurological patients. It is known that stroke survivors have a limited amount of degrees of freedom (DOF) of the hemiparetic arm due to synergistic movement patterns. [14, 15] Stroke survivors generally experience difficulties of single or multi-joint movements requiring extension of the elbow, due to the flexion synergy consisting of a combination of elbow flexion and shoulder abduction. If motor adaptation is influenced by movement direction in stroke survivors as well could have implications for future stroke rehabilitation.

In this explorative study we did observe a difference in amount of adaptation between different directions, which should be studied in more detail in future research. Examples are calculating the rate of adaptation by means of curve fitting instead of the amount of adaptation. Also data of healthy elderly and stroke survivors would be essential to test whether observed results are present in these populations as well, which could have implications for motor relearning in rehabilitation therapy.

**V. CONCLUSION**

Subjects show larger adaptation to -72 directions at peak velocity compared to other directions. When possible feedback and corrections mechanisms are taken into account; results indicate that subjects adapt most towards -72 direction, and least towards -144 direction. Data consisting of the constitution of different movement directions in one learning curve should be analyzed with care while movements into different directions seemed to be learned differently.

**ACKNOWLEDGEMENT**

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**REFERENCES**

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